NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

EVALUATION OF LITTORAL COMBAT SHIPS FOR OPEN-OCEAN ANTI-SUBMARINE WARFARE

by

Team LCS
Cohort 311-143O

March 2016

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1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE March 2016	3. REPORT TYPE AND DATES COVERED Capstone project report	
4. TITLE AND SUBTITLE EVALUATION OF LITTORAL COMBAT SHIPS FOR OPEN-OCEAN ANTI-SUBMARINE WARFARE		**5. FUNDING NUMBERS**	
6. AUTHOR(S) Team LCS, Systems Engineering Cohort 311-143O			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000		**8. PERFORMING ORGANIZATION REPORT NUMBER**	
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A		**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**	

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number _____N/A_____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

    This report evaluates the Littoral Combat Ship (LCS) and its potential to fulfill the open-ocean anti-submarine warfare (ASW) mission. It is unknown whether the LCS platform can support open-ocean ASW. This report examines which LCS variant, Freedom or Independence, is more suitable for open-ocean ASW. Initial analysis defines the open-ocean ASW problem space in terms of a threat analysis, mission analysis, current Concept of Operations (CONOPS), and current LCS capabilities. An Analysis of Alternatives (AoA) uses derived functional and operational requirements within a Pugh matrix to decide which variant best performs ASW, and what modifications can improve future designs of the LCS. The analysis shows the Freedom class has marginal advantages in performing open-ocean ASW mission tasks, and establishes three areas for improvement: self-noise emissions, weight, and communication. Potential solutions are explored to address these shortfalls and to analyze their impact on LCS's ability to meet core requirements of the open-ocean ASW mission. This paper concludes that the LCS is capable of fulfilling the open-ocean ASW mission if improvements are made to the design and CONOPS.

14. SUBJECT TERMS anti-submarine warfare, littoral combat ship, mission module, systems engineering, requirements development, architecture, capability, functional decomposition, modeling and simulation, ASW, LCS			**15. NUMBER OF PAGES** 99
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

i

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EVALUATION OF LITTORAL COMBAT SHIPS FOR OPEN-OCEAN ANTI-SUBMARINE WARFARE

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Submitted in partial fulfillment of the
requirements for the degrees of

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NAVAL POSTGRADUATE SCHOOL
March 2016

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ABSTRACT

This report evaluates the Littoral Combat Ship (LCS) and its potential to fulfill the open-ocean anti-submarine warfare (ASW) mission. It is unknown whether the LCS platform can support open-ocean ASW. This report examines which LCS variant, Freedom or Independence, is more suitable for open-ocean ASW. Initial analysis defines the open-ocean ASW problem space in terms of a threat analysis, mission analysis, current Concept of Operations (CONOPS), and current LCS capabilities. An Analysis of Alternatives (AoA) uses derived functional and operational requirements within a Pugh matrix to decide which variant best performs ASW, and what modifications can improve future designs of the LCS. The analysis shows the Freedom class has marginal advantages in performing open-ocean ASW mission tasks, and establishes three areas for improvement: self-noise emissions, weight, and communication. Potential solutions are explored to address these shortfalls and to analyze their impact on LCS's ability to meet core requirements of the open-ocean ASW mission. This paper concludes that the LCS is capable of fulfilling the open-ocean ASW mission if improvements are made to the design and CONOPS.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADM	advanced development model
AIP	air independent propulsion
ALFS	airborne low frequency sonar
AoA	analysis of alternatives
ASW	anti-submarine warfare
CG	Cruiser ship
CNO	Chief of Naval Operations
CONOPS	concept of operations
CSP	commence search point
CV-TSC	Aircraft Carrier tactical support system
dB	decibel
DDG	Destroyer ship
DI	directivity index
DOD	Department of Defense
DT	detection threshold
EDM	engineering development model
EPA	Environmental Protection Agency
FFG	Frigate ship
FLIR	forward looking infrared radar
FOM	figure of merit
FY	fiscal year
GAO	Government Accountability Office
HVU	high value unit
ISAR	inverse synthetic aperture
LCS	Littoral Combat Ship
LDR	laser rangefinder designator
LWT	Light Weight Tow
MCM	mine countermeasures
MFTA	multi-function towed array
MMCS	Multi Mission Combat Ship

MPAS	mission package application software
NL	noise level
NPS	Naval Postgraduate School
PAMS	Passive Active Multistatic Search
PC	Patrol Coast ship
PD	probability of detection
PRAIRIE	Propeller Air Internal Emission
R	range
ROK	Republic of Korea
S	search width
SCS	Surface Combat Ship
SE	signal excess
SL	source level
SNR	signal to noise ratio
SSC	Small Surface Combatant
SUW	Surface Warfare
TCDL	tactical common data link
TDM	torpedo defense module
TL	transmission loss
TS	target strength
U.S.	United States
USN	United States Navy
VDS	variable depth sonar
VLS	vertical launch system
VTUAV	vertical takeoff unmanned aerial vehicles

EXECUTIVE SUMMARY

The Littoral Combat Ship (LCS) class of ships were designed to be small, fast, and agile platforms that operate within the littoral environments. This paper explores which variant of LCS is best equipped to perform Anti-Submarine Warfare (ASW) in an open-ocean environment. This report also identifies what improvements can enhance LCS ASW mission effectiveness. Open-ocean ASW missions require searching and engaging submarine threats in deep-water environments over large areas, a mission the LCS was not originally intended to fulfill.

This report analyzes the problem space of the LCS performing open-ocean ASW in terms of a threat, mission, and current capabilities analysis. Threat analysis shows that diesel-electric and nuclear submarines from North Korea, China, and Russia are the main threats to U.S. security that the LCS may have to prosecute. According to a *China Daily News* article published in October 2014, some of these threats can operate at depths up to 600 meters and have self-noise emissions below 110 dB. Mission analysis defines functional and operational requirements for both general ASW and open-ocean ASW. The analysis focuses on addressing the specific requirements for open-ocean ASW such as transit distance, time on station, and accuracy and range of threat detections. The paper also focuses on weight and self-noise emissions, which are current problems for LCS in the littorals, but worsen when in an open-ocean environment.

Three capability gaps have been identified that limit the LCS in performing open-ocean ASW. Endurance is an overarching capability that covers how long the LCS can be on mission, whether it is in transit or holding station. Fuel is the limiting factor for endurance for the LCS. To address the gap in endurance, the report explores the impact of weight, fuel storage, and fuel consumption on overall endurance. Modeling shows that the use of MH-60R helicopters equipped with AQS-22 sonars greatly extend the range and accuracy of threat detections.

This paper analyzes three categories of potential upgrades to LCS. Expanding the LCS data link capabilities would permit better integration of sensor data and coordination

of multi-platform efforts. Additionally, LCS does not have radiated noise reduction or silencing features. Therefore, radiated noise reduction features like Propeller Air Internal Emission (PRAIRIE) and Masker systems, using machinery isolation mounts, and operational changes should be made to reduce the LCS acoustic signature. This report examines LCS modifications, which improve endurance and range.

Utilizing the investigation into LCS capability gaps and open-ocean ASW requirements, this report provides several recommendations on how the LCS can meet these requirements. The report concludes that with the suggested improvements, the Freedom class LCS is capable of performing open-ocean ASW, and can meet the endurance and threat-detection requirements necessary for this mission.

ACKNOWLEDGMENTS

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I. INTRODUCTION

A. BACKGROUND

The Littoral Combat Ship (LCS) class of ships, illustrated in Figure 1, were designed to be small, fast, and agile with the ability to adapt to modern conflicts in shallow water. The ships are capable of neutralizing asymmetrical threats that exist in the littoral battle space such as small boats, quiet diesel-electric submarines, and mine threats. Each variant is different and built by different contractors.

Figure 1.   The Two LCS Variants, USS Freedom (left) and USS Independence (right)

Adapted from Sam LaGrone, 2013, "LCS Mission Packages: The Basics," U.S. Naval Institute, http://news.usni.org/2013/08/21/lcs-mission-packages-the-basics.

Lockheed Martin and Marinette Marine build the Freedom variant, while the Independence variant is built by General Dynamics and Austal USA. Both LCS variants were designed to utilize modular-based mission packages that support different surface ship operations: Surface Warfare (SUW), Mine Countermeasures (MCM), and Anti-Submarine Warfare (ASW). In order to fulfill operational requirements, the current Freedom and Independence LCS depend upon three mission packages for different warfare areas. Figure 2 illustrates these. The SUW mission package offers capability for neutralizing small-boat threats and providing littoral security. The ASW mission package provides capability for submarine detection, classification, and neutralization. The final package, MCM mission package, provides capability for detection and neutralization of deployed mines. Each ship is to be equipped with the mission package tailored to the

mission tasking and must be installed prior to the ship leaving port. Personnel can exchange the mission packages on the sea frame in a short time. This allows for quick responses to changing threats. The mission package paradigm permits a smaller vessel, utilizing modular designs, to serve in many roles against changing threats.

Figure 2.   LCS Mission Packages

Systems that entail the three mission packages of the LCS. Adapted from Government Accountability Office, 2014, "Littoral Combat Ship, Additional Testing and Improved Weight Management Needed Prior to Further Investments," http://www.gao.gov/assets/670/665114.pdf.

Initially, the United States Navy (USN) planned to procure 52 of the LCS class of ships and to have delivery of the first sea frame in FY2005 (O' Rourke 2015a). Subsequently, USN reduced this initial number to 40 vessels, according to a memo from Defense Secretary Ash Carter dated December 14, 2015. Additionally, according to a press release issued by former Secretary of Defense Charles Hagel on December 11, 2014, the original LCS designs have been rigorously re-evaluated identifying improvements to the design. Navy personnel performed the evaluation of both LCS variants, in order to determine if modified versions of the vessels could fill the role of a frigate. Hagel states that the original LCS designs could be improved upon by increasing both ship lethality and survivability. Additional areas of potential improvement for the initial LCS variants are identified in Figure 3; they included a variable-depth sonar (VDS), torpedo countermeasures, anti-ship missile defense system, surface-to-surface missiles, radar, electronic warfare system, guns, and Multifunction Towed Array

(MFTA). According to Hagel, these improvements would permit a more survivable LCS with increased sensor capability.

Figure 3.   Follow-on Class Requirements
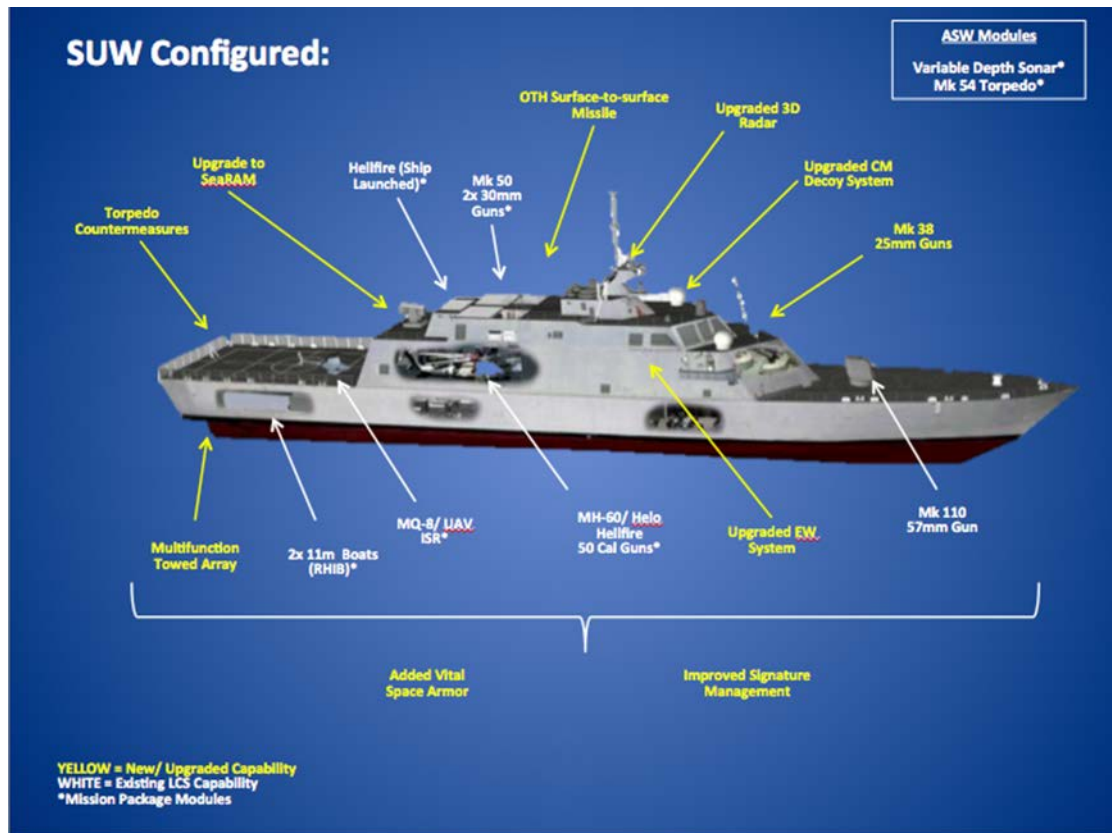
Adapted from Christopher P. Cavas, 2014, "A closer look at the "Modified LCS," http://intercepts.defensenews.com/2014/12/a-closer-look-at-the-modified-lcs.

In addition to the analysis and improvements of LCS suggested by USN personnel, each of the prime contractors associated with both LCS variants have proposed improvements to their original LCS designs.

Lockheed Martin, a contractor associated with the Freedom variant, has proposed three potential follow-on designs to the LCS shown in Figure 4, and are named the Small Surface Combatant (SSC), the Surface Combat Ship (SCS), and the Multi-Mission Combat Ship (MMCS) variants. These vessels are intended for export as well as potential domestic uses.

The Small Surface Combatant variant is designed to have enhanced defensive systems and more firepower in order to focus on surface and air targets. There exists less emphasis on the multi-role capability that mission packages provide, and more emphasis on standalone systems. The SSC can support surface and air warfare missions and removes mission package systems from the sea frame.

The proposed Surface Combat Ship variant will include an Aegis combat system used in national missile defense.

The Multi-Mission Combat Ship variant has been designed with a smaller hull and will be operated by a smaller crew. The primary mission of the MMCS will be as a patrol vessel (Sweetman 2008, 7). This class is smaller and slower than the current LCS variants and can support border protection and counter-piracy missions (General Dynamics 2015).

Figure 4.   Potential LCS Freedom Follow-on Designs

Follow-on designs to the LCS are named the Small Surface Combatant (SSC) (bottom of figure), the Surface Combat Ship (SCS) (middle of figure), and the Multi-Mission Combat Ship (MMCS) (top of figure) variants. Source: *Defense Industry Daily*, 2015, "LCS: The USA's Littoral Combat Ships," http:// http://www.defenseindustrydaily.com/the-usas-new-littoral-combat-ships-updated-01343/.

General Dynamics, the prime contractor of the LCS Independence variant, has also proposed follow-on designs. Follow-on LCS Independence variants are to serve as

either a small surface combatant or a border patrol and counter piracy vessel. Discussion of these variants has been included to illustrate potential future roles LCS may fill.

B. PROBLEM STATEMENT

In FY2014, by the direction of the secretary of defense, the LCS program was restructured (O' Rourke 2015a). According to O'Rourke, to fill the capability gap left by the decommissioning of all U.S. Naval Frigate–class ships, the last 20 LCS class ships will have a Frigate classification and improved capabilities relative to the base LCS design. O'Rourke also indicates that the new Frigate design enhancements will focus on SUW and ASW operations. Additionally, O'Rourke claims that the current fleet of existing LCSs will carry out MCM operations. As the original LCSs were not designed for open-ocean ASW operations, it is unknown if the restructured program is viable. That is, there is no evidence or analysis to support or refute the LCS's ability to carry out this new mission. Further, it is unknown which variant (Freedom or Independence) is more suitable for the mission. Additionally, it is likely that some ship or mission package modifications would be required. However, no one yet knows what equipment or Concept of Operations (CONOPS) would be affected. Therefore, it is not possible to make informed programmatic decisions based on improved capabilities versus their associated costs.

C. RESEARCH OBJECTIVE

The objective of this report is to determine whether the LCS can execute open-ocean ASW missions. One aspect of the evaluation is an Analysis of Alternatives (AoA) to determine if one variant is better than the other is at performing open-ocean ASW. This report makes recommendations on how to improve that variant for open-ocean ASW. In addition to a CONOPS, requirements for open-ocean ASW for LCS were developed. This report provides answers to the following research questions:

(1)   Which LCS variant performs open-ocean ASW better?

(2)   What changes need to be made to the LCS to facilitate effective open-ocean ASW?

(3)   How effective will the proposed solution be at open-ocean ASW?

(4)   How much will the proposed solution cost?

(5)   How much more effective will the proposed solution be compared to the current LCS platforms?

This report provides a feasibility study on whether the LCS platform is suitable for conducting open-ocean ASW with the assumption that the LCS platform can adequately defend itself. Additionally, this report identifies capability gaps existing between the requirements of open-ocean ASW and the current capability of the LCS.

Big-budget military programs often attract scrutiny from the public. Public opinion influences political decisions, which have significant impacts upon military programs. The results of the study serve to inform the public on whether or not the LCS platforms' potential open-ocean ASW mission is a worthy investment of their tax dollars.

D.   SYSTEMS ENGINEERING PROCESS

The capstone report team utilized an iterative systems engineering process model when answering the research questions. The team approached the research questions with an open mind, explored all possible solutions, and developed a recommendation to best utilize LCS for open-ocean ASW. The iterative process focused on analysis of the problem space, identifying system requirements, analysis of the system elements and analysis of mission effectiveness. Figure 5 illustrates this process and the interactions of each step.

Figure 5.   Systems Engineering Process
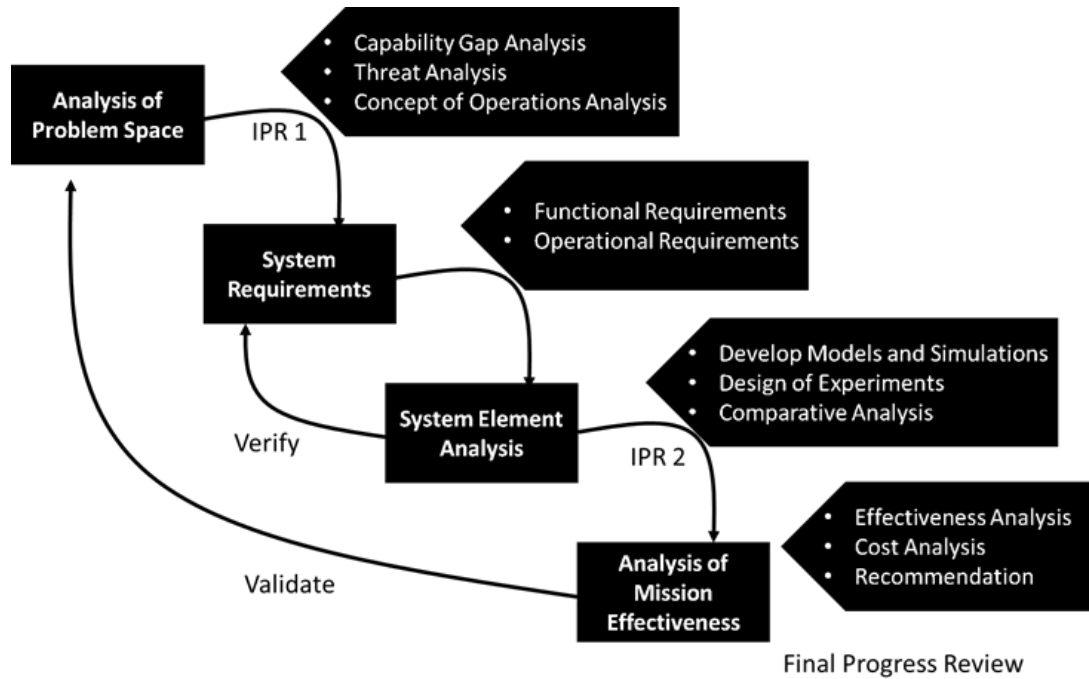
(1)   Analysis of Problem Space

This research team identified and analyzed problems associated with the capability caps of the LCS in conducting open-ocean ASW. Additionally, a high-level threat analysis was performed to establish the threats that are associated with open-ocean ASW. The current mission packages and CONOPS performed by the LCS were analyzed in order to determine the differences between performing ASW in littoral environments versus the open-ocean environment. The results from the problem space analysis were utilized as the basis for the System Requirements.

(2)   System Requirements

The open-ocean ASW requisites were translated into system requirements. The CONOPS was transformed into verifiable requirements that define what the system will do but not how the system will do it.

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(3)   System Element Analysis

Potential new system elements that need to be either included or developed, modifications to existing system elements, and modifications to the existing sea frame were identified in order to find solutions that met the requirements established in the earlier section. The two variants of the LCS were compared against each other in order to determine if one variant was more capable than the other in performing open-ocean ASW. System elements and mission packages, as well as potential mission packages, were analyzed in order to determine the best possible solutions meeting the system requirements.

(4)   Analysis of Mission Effectiveness

The various LCS system elements were matched to the established requirements and to the requirements addressed in the problem space analysis. Costs analysis was performed in order to evaluate the cost estimates and performance associated with the proposed solutions. The engineering process concludes with a recommendation on the best solution.

II. PROBLEM SPACE EXPLORATION

A. HISTORY OF ANTI-SUBMARINE WARFARE

With the advent of the submarine, naval warfare was forever changed. No longer were threats on the surface of the water but also below. Initial submarines were surface ships that would occasionally submerge. A submarine on the surface with all of her propulsion systems operating was easily detectable, but submerged with few systems operating, a submarine was a significant and quiet threat. As shipbuilders added nuclear power capabilities to submarines, the sub went from spending most of her time on the surface to being submerged for extended periods and being capable of launching weapons without coming to the surface. Submarines were also built to be quiet in the water, reducing the noise that could be exploited to detect her. ASW was a game of cat and mouse, reduced to detecting and neutralizing an enemy submarine before her weapons could be used.

Off-board sensors were also developed that passively could detect enemy submarines. Passive systems increased the range at which detections occurred which gave commanders more time to engage an enemy and neutralize the sub before her weapons were used. Maritime patrol aircraft were also used in ASW. Aircraft were speedy platforms that could respond quickly to detection and initially localize the contact. Once localized, other platforms would be passed the information and engage the enemy submarine. The key to success in ASW was to be acoustically quieter than the enemy thereby detecting before being detected.

B. THREAT ANALYSIS

The success of the LCS mission to conduct ASW in the open ocean is dependent upon the capabilities of the threats that she will be prosecuting. There exists a large variety of submarines produced by many nations. Determining the threats that the LCS platform will need to prosecute is a matter of determining nations with which the U.S. has a less-than-friendly relationship and with which may have poor relationships in the future. To further focus this list, we have examined both unfriendly countries (see Table 1

for list of countries operating submarines), and those with the capability to threaten our interests through submarines with open-ocean capability.

Table 1.   Nations Operating Submarines

Algeria	Argentina	Australia	Bangladesh	Brazil	Canada	Chile	**China**	Columbia
Ecuador	Egypt	France	Germany	Greece	India	Indonesia	Iran	Italy
Israel	Japan	Malaysia	Netherlands	**North Korea**	Norway	Pakistan	Peru	Poland
Portugal	**Russia**	Singapore	Sri Lanka	South Africa	South Korea	Spain	Sweden	Taiwan
Turkey	United Kingdom	Venezuela	Vietnam					

Nations in bold operate submarines that were considered in detail for this report. Adapted from Michaele Lee Huygen, 2003, "Submarine Warfare in the 20th & 21st Centuries: A Bibliography," report, Naval Postgraduate School

Of the forty nations that currently operate submarines, based upon current and potential future relations, seven of those nations may hold conflicting military interests with the United States. While Egypt, Iran, Pakistan, and Venezuela are taking steps to improve their submarine fleet, they do not yet have the capability in the near or midterm to pose a threat to U.S. interests. This analysis will focus upon the greatest undersea threats, those posed by China, North Korea, and Russia.

China and Russia both field a fleet of a large variety of submarines. This analysis will focus on a subset of these threats, threats believed to be of either the most lethal, or the most populous. In particular, this report examines the propulsion types of these threats, as these propulsion types change the way a submarine operates, and this behavior can be exploited through prosecution tactics.

1.   **North Korea**

While North Korea's fleet has aged over the years, it is determined to attack our South Korean ally when it calculates that the benefit far exceeds the risk: "[North Korea's] submarine force, unsophisticated but durable, demonstrated its capabilities in March 2010 when it covertly attacked and sank the ROK warship Cheonan with an indigenously produced submarine and torpedo" (Office of the Secretary of Defense 2013). The submarine that ROK deployed to sink the Cheonan was a midget-class submarine that does not have open-ocean capability. This provocation does demonstrate North Korea's resolve to attack the U.S. and her allies. North Korea is a nuclear-armed power, and has been developing the capability to deploy nuclear weapons via ballistic missiles, possibly through Vertical Launch System (VLS) equipped submarines (Office of the Secretary of Defense 2013).

North Korea's navy is one of the world's largest submarine forces, with approximately seventy attack-, coastal-, and midget-type submarines (Office of the Secretary of Defense 2013). They have stated that the capability to strike the U.S homeland is one of their military objectives. North Korea claims to have successfully test fired a ballistic missile from an indigenously built submarine, demonstrating its growing capability as a threat (*Daily Mail* 2015). The LCS will have to be able to prosecute submarines currently existing in North Korea's fleet, and those that it is actively working to procure.

a.   Romeo Class Submarine

The Romeo class submarine, which is built by the former Soviet Union, makes up the bulk of the North Korean submarine fleet. It operates an estimated 77 Romeo class submarines (Bermudez 2014). Bermudez states that these submarines were built in the 1950s, and are aging. They are not sophisticated and represent Soviet technology developed in the early years of the Cold War. They are slow, sailing at 15.2 knots at maximum speed while surfaced (Global Security 2016c). They have diesel-electric propulsion. Diesel-Electric, while having become much quieter in recent years, used to be a large source of noise in the 1950s. That, coupled with immature sound dampening

technology, makes the Romeo class easily detected. However, as Global Security states that they have a surfaced range of 9,000 nautical miles, they are able to operate in the open ocean. Combined with the large population of Romeos in North Korea's fleet, they remain an attrition threat that the LCS will have to prosecute successfully in a military conflict.

b.   *Sang-O Class Submarine*

The Sang-O class submarine is a much quieter diesel-electric than the Romeo. It is an indigenously built submarine, first constructed in the 1990s. This is a reflection of more advanced, but not quite modern, improvements in sound dampening and diesel-electric technology (Global Security 2016d). North Korea operates approximately 40 Sang-O submarines. Global Security states that the Sang-O is a much slower submarine than the Romeo; however, it is a coastal platform. While this report is only concerned with open-ocean platforms, the Sang-O is investigated as it can operate at 1,500 nautical miles, which allows operation within open oceans near American allies. The Sang-O is equipped with Russian Type 53 torpedoes, which are especially lethal, as countermeasures are not effective against them (Bermudez 2011).

c.   *Sinpo Class Submarine*

The Sinpo class submarine is a new class of submarine that is currently under construction. It is the largest of the North Korean built submarines. It may be a replacement for the Romeo class, but it could also be experimental (Bermudez 2015). The Sinpo will represent a significant step forward for North Korea's submarine fleet. Additionally, it is possible that North Korea will outfit it with an Air Independent Propulsion (AIP) system (Keck 2015). Keck states that AIP systems allow submarines to stay submerged while charging their battery system. Traditional diesel-electric systems require submarines to surface in order to charge their battery system. During this time, the submarine is more vulnerable to prosecution than when submerged. AIP eliminates the vulnerability of traditional diesel-electric systems, allowing the submarine to continuously operate under the surface. Bermudez states that it is very likely that the Sinpo have the Vertical Launch System (VLS), and much evidence points towards its role

as a ballistic missile submarine. VLS provides the capability for a greater variety of weapon systems to submarines, improving their lethality.

2.   People's Republic of China

China is neither an enemy nor an ally of the U.S. It does have conflicting military and geopolitical interests, however, and its growing capabilities are providing them with the confidence necessary to embolden them. They have territorial claims within disputed waters to which U.S. allies have claim, and they have long sought to annex Taiwan, a strong American ally. China has one of the largest militaries in the world and is funded by the second-largest economy in the world.

China has demonstrated that it has the capability to take the U.S. by surprise. In November 2006, a Chinese submarine surfaced within firing range of the USS Kitty Hawk (CV-63) before being detected (Gertz 2006). Chinese capabilities and training regimen have grown more advanced since then. Its military is heavily investing in weapons designed to defeat American capabilities that it believes threatens its interests in the Pacific. Much of its investment has been used to advance its already diverse submarine fleet. It seeks to establish a new relationship, with American interests being subordinate to theirs. Figure 6 shows a Russian-made submarine purchased by China.

Figure 6.   China's Kilo Class Submarine

Adapted from Lindsay Hughes, 2015, "Dragon vs Elephant, Chinas Offensive Naval Ambitions and Strategies," http://defencyclopedia.com/2015/07/17/dragon-vs-elephant-part-3-chinas-offensive-naval-ambitions-and-strategies/.

a.   *Kilo Class Submarine*

The Kilo class submarine is a Russian-built submarine first constructed in the 1980s. China acquired its first Kilos during the mid-90s, and had twelve in active service as of 2006 (Erickson, Goldstein and Murray 2007). According to Erickson, the Kilo is designed for anti-surface and anti-submarine warfare. Additionally, Erickson claims the Kilo can be equipped with surface to air missiles, which potentially allows it to target enemy aircraft. Erickson states that the Kilo can reach speeds of 12 knots while surface, 25 knots while submerged, and 7 while snorkeling. It is a diesel-electric submarine. While the Kilo is not a very quiet diesel-electric submarine, new variants are coming with modern sound dampening equipment. Additionally, Erickson suggests that like many diesel-electric submarines, it is possible that it can be equipped with an AIP system, enhancing its lethality through mitigation of detectability. With a range of 7500 nm, the Kilo easily can traverse the open ocean (Naval Technology 2016).

b.   Song/Yuan Class Submarines

The Song and Yuan class submarines are Chinese-built submarines, with the first Song being constructed in the 1990s. China operates an estimated twelve active Songs, one hundred fifteen Active Yuans, with five Yuans under construction (Erickson, Goldstein and Murray 2007) . These are diesel-electric submarines, but some Yuans have been equipped with AIP technology. All Song and Yuans can be equipped with AIP. These ships are capable of traversing through the open ocean at 22 knots submerged (Global Security 2016e). They are heavily armed, anti-surface warfare ships, which have a maximum range of 8000 nautical miles, according to Global Security. As described earlier, the Song, which is less advanced than the Yuan, took the USS Kitty Hawk (CV-63) by surprise in November 2006. It surfaced within firing range, before being detected (Gertz 2006). This demonstrated its capabilities, as well as the capabilities of the Chinese sailors on board. The Yuan is more capable, being able to submerge at greater depths, traverse at high speeds, and operate more quietly than its predecessor, Song.

c.   Shang Class Submarine

The Shang class submarine is a modern nuclear powered Chinese-built submarine first constructed in the 2000s. China has completed five of these platforms, with two currently active, and one under construction (Global Security 2016f). The Shang is a fast nuclear submarine, being able to operate at 30 knots (Military Today 2016b). It is heavily armed with torpedoes, and boasts a VLS, allowing it to attack both subsurface and surface targets, according to *Military Today*. As a nuclear submarine, it can operate for as long as supplies exist for the crew, effectively making its range virtually unlimited. It can submerge to depths as deep as 400 meters and is a very quiet nuclear submarine (Global Security 2016f). The Shang represents a significant milestone in the Chinese submarine program, which continues to make more advances in the undersea realm.

d.   Type 095 Class Submarine

The type 095 class Submarine, under development, is a future nuclear-powered attack submarine. It will be able to operate in the open ocean, will be equipped with VLS and have a significantly reduced acoustic signature (Lin and Singer 2015). According to

Lin and Singer, more than likely, it will be quieter than the Shang, putting it at less than 110 dB. It is considered to be a "carrier killer," as it will probably be equipped with the YJ-18 anti-ship missile, which was "specifically designed to defeat the Aegis Combat System" (Gady 2015). China claims that the 095 will have a minimum submerged speed of 33 knots, with a minimum silent cruise speed of 18 knots (Yee 2014). Yee also states that it will be able to reach depths as great as 600 meters and that the Type 095, if Chinese claims are accurate, will be comparable to, if not better than the United States' Virginia and Seawolf class submarines. While experts believe these claims may be inaccurate, the Type 095 represents a significant threat to United States' interests, a threat the LCS must be successful in defeating.

3.   Russia

Russia has a complicated and turbulent relationship with the U.S. Before the Cold War ended in 1991, Russia, the former Soviet Union, was the United States' main military and geopolitical rival. The two nations spent billions engaged in proxy wars against each other and were in a constant arms race for supremacy on land, air, space, and the undersea domain: "Since the early 2000s, high oil revenues have given Russia the opportunity to start recapitalizing and modernizing its military, which have resulted in a recent increase by 150 percent in spending for Russia's strategic nuclear forces, and the setting aside of $160 billion for procurement of new naval ships and submarines until 2020" (Nuclear Threat Initiative 2014).

The following analysis illustrates that the Russian submarine fleet is a diverse mixture of both aging and modern platforms. Russian weapon systems are varied and capable. Russia is considered the only military peer to the U.S. and has the experience and growing will to re-establish itself on the global stage and project its power across the world.

a.   *Romeo Class Submarine*

The Romeo was discussed earlier as part of the North Korean submarine fleet. Russia has built the Romeo class, and has exported it across the world as a part of its defense industry. As the Romeo was once a highly capable platform, Russia's fleet is host

to a great many of this aging platform. According to Global Security, Russia employs fifty-eight active Romeos within its fleet. These ships are being replaced. While the Romeo is not a highly capable platform, Russia fields a great many, and continues to manufacture this class with modern upgrades (Global Security 2016c).

b.   Kilo Class Submarine

The Kilo class submarine was discussed earlier as part of the Chinese submarine fleet. Russia builds the Kilo class, and has exported it across the world as a part of its defense industry. Russia employs fifteen Kilo submarines (Naval Technology 2016). This platform is more capable than the Romeo but is also considered to be an aging submarine. Even so, the Kilo remains a threat to the U.S. interests.

c.   Akula Class Submarines

The Akula class is a submarine built in Russia from technologies from the 1980s and improved in the 1990s (Military Today 2016a). Russia fields nine Akula submarines. They are nuclear-powered, can reach speeds as fast as 35 knots while submerged, and have an unlimited range (Military Today 2016a). These heavily armed submarines can target submarine, surface, and air threats. The Akula can dive to depths as great as 480 meters (Military Today 2016a).

d.   Lada Class Submarine

The Lada class is a diesel-electric successor to the Kilo. It is a more silent, improved Kilo, with the potential to be equipped with AIP. Russia currently fields one Lada, is building two now, and plans to build eight more (Global Security 2016a). They designed it for anti-surface and anti-submarine warfare. According to Global Security, the Lada can reach 21 knots while submerged, and 10 knots while surfaced. Global Security also states that the Lada has a depth of 300 meters and that its range is not known, but given that it is an improved Kilo, it is highly probably that it will operate in the open ocean. As with many Russian platforms, not much more is known. Considering that this platform is currently built, and assuming it is designed with modern

technologies, it is probable that the Lada operates at less than 110 dB, possibly significantly less (Global Security 2016a).

e. *Yasen Class Submarine*

The Yasen class submarine is a modern Russian attack submarine employing the latest developments in submarine technology. It is projected to replace both the Akula and Oscar class submarines. It is a nuclear-powered submarine, which allows it unlimited range. It is heavily armed, equipped with VLS, and able to attack surface, subsurface, and land targets. Russia has completed production of two Yasens, they have fielded one, and are currently building four more with twelve planned for production (Global Security 2016b). The Yasen is a threat in the open ocean and will be the most advanced platform the LCS may encounter.

C. MISSION ANALYSIS

1. Open Ocean vs. Littoral ASW

The ASW systems and practices employed in the open ocean are not necessarily those that work best in littoral waters.

> Littoral ASW requires a complementary set of capabilities that address the special circumstances of naval operations in littoral waters. The littoral battlespace's complex, noisy environment undermines the effectiveness of acoustic ASW sensors optimized for deep water, open-ocean ASW. In this environment, increasingly quiet and capable submarines operated by potential adversaries further erode the position held by open-ocean ASW forces. Quiet threats operating in harsh environments increase the utility of non-acoustic and active acoustic sensor systems. To be effective, sensors must be able to automatically adapt to the environment. (Department of the Navy 1998, Mission and Tasks)

As ASW changes and evolves to the modern world, the current use of sensor-based systems to fulfill the ASW mission may not be very effective. To respond to this new threat, a new approach has emerged called "Full Spectrum ASW" (Toti 2014). Full Spectrum ASW pursues a more holistic approach to solving anti-submarine warfare missions. ASW becomes about defeating the submarine which can be done in many ways.

For example, [operations] in the vicinity of mines is possible without destroying all of them. All that is needed is that there are no mines near you and that you have a clear sea lane. Undetected but irrelevant mines become a nuisance but are not a threat. Diesel submarines can be thought of as smart, somewhat mobile, mines. … Targets of diesel submarines can easily outrun and out endure their nemeses. To defeat the submarine, all that must be done is to render [the sub] irrelevant. (Toti 2014)

Defeating the submarine can be accomplished by one or more of the following: taking it out of a firing position, making its fire control solution to be incorrect, having it pursue a different target, or rendering its weapons useless (Toti 2014). Open-ocean full spectrum ASW accomplishes these solutions to the problem.

2.   Open-Ocean ASW Mission

Figure 7 provides a visual breakdown of the core mission areas within ASW, which consist of three main tasks: locating a target submarine, engaging, and surviving a possible counterattack. Locating a submarine consists of three subtasks: Detect, Localize, and Target. Detection is the capturing of noise and signal of a target submarine and classifying it as a contact. Localization is the establishment of the contact's location to within a reasonably small area. The determination of a submarine's bearing to ownship, range, and speed allows classifying the contact as a target. Once classifying the submarine as a target, it can be engaged directly or through other support vehicles. In addition to prosecuting a target, successful implementation of ASW requires the ability to survive an attack from the target, should the submarine be able to launch one.

Figure 7.   Breakdown of ASW into Core Mission Areas and Mechanisms
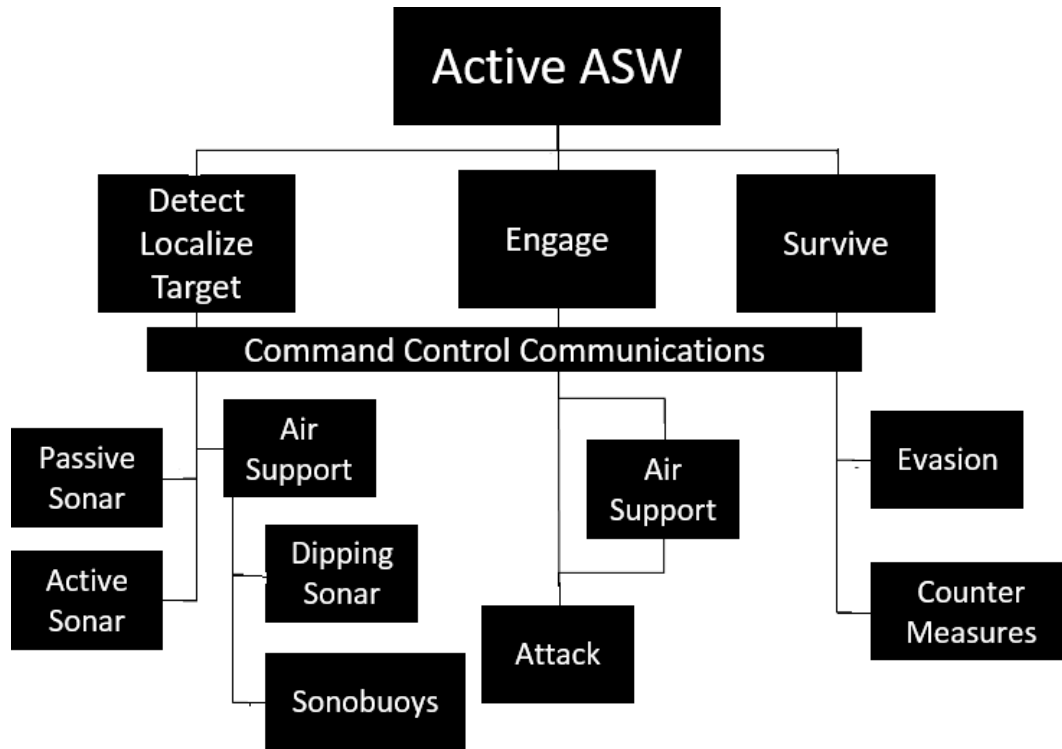
The detection, localization, and targeting of a submarine is also known as searching for a submarine. Present CONOPS leverages passive sonar as the initial and primary form of searching. Passive sonar systems listen for acoustic anomalies in the surrounding environment. While searching for a threat, a platform must generate as little self-noise as possible. Self-noise, which is noise that a platform generates from crew and equipment, interferes with the radiated noise of a target submarine. An abundance of self-noise can alert the threat to the prosecuting platform, or prevent that platform from detecting the threat.

If a platform, or in the context of this report, the LCS, is able to detect a threat, but there does not exist enough information to classify the source of the detection, the LCS can deploy a helicopter with a dipping sonar. This helicopter can increase the chances of localizing and classifying the contact, as it is able to change its position very quickly, and its dipping sonar activity generates little underwater noise. The helicopter

can perform a parallel search pattern in order to increase the likelihood of contact localization. Figure 8 shows that a parallel pattern search equally searches across an area. The helicopter submerges its dipping sonar at the commence searching point (CSP), and then transits a distance known as the search leg. At the end of each leg, the helicopter will use its sonar capabilities to listen for the contact. At each leg, the helicopter will turn 90 degrees to transit a new leg for a distance equal to the search width of the sonar system being used. This search width is denoted by the S in Figure 8 and Figure 9. Again, the helicopter turns 90 degrees so that it returns to the search area and continues the search leg. Repeating this pattern allows the helicopter to cover an area that is one-half its search width larger in all directions, denoted by the S/2 space between the search area boundary and actual search path.

Figure 8.   Parallel Pattern Search
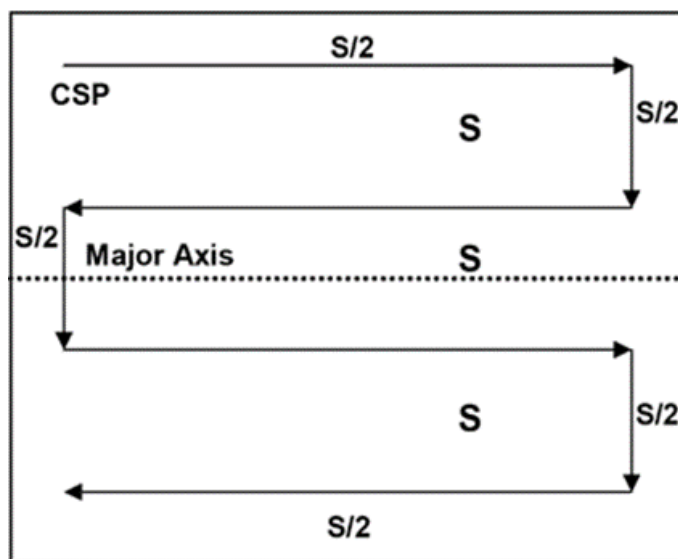
Used for a large-area search when the target location is not well known. Source: R. R. Hill, R. G. Carl, and L. E. Champagne, "Using Agent-Based Simulation to Empirically Examine Search Theory Using a Historical Case Study," *Journal of Simulation*, December 1, 2006: 29–38.

If there exists a high confidence in the location of the contact, a square search pattern can be used to assist in the classification of the contact, as well as forming a target solution. The square search CSP begins where the detection was believed to originate and

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spirals outward. As shown in Figure 9, the searchers increase the search leg every other time. This creates an outwards spiraling effect that provides high coverage in the area immediately around the CSP.

Figure 9.   Square Search Pattern
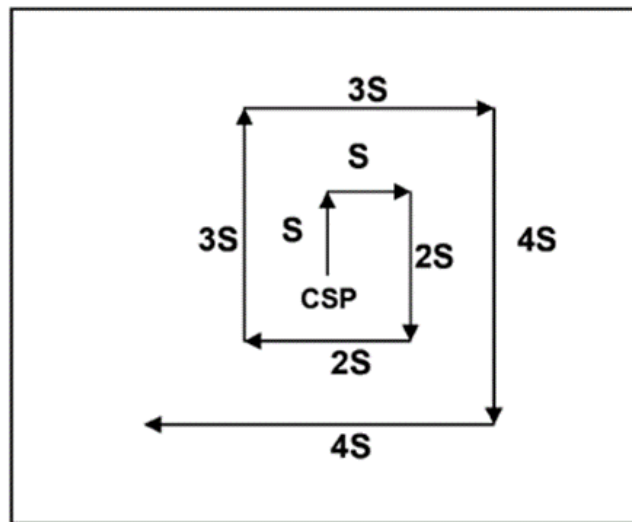
Used to provide high coverage over a small area. Source: R. R. Hill, R. G. Carl, and L. E. Champagne, "Using Agent-Based Simulation to Empirically Examine Search Theory Using a Historical Case Study," *Journal of Simulation*, December 1, 2006: 29–38.

Once a detection has been made, it is critically important to properly classify that contact. Classification involves determining the source of the detection and whether or not that contact should be investigated. For example, the detection of a school of fish or a pod of whales is not worth investigating and would only hinder ASW operations. In order to avoid problems such as this certain parameters are required before classification can begin. For classification the parameters are a number of pings and the accuracy of the contact returns.

After proper classification, if passive sonar systems have not yet localized or targeted the contact, active sonar systems can be leveraged. Active sonar transmits acoustic energy into the water, known as a "ping." These systems generate pings and listen for the reverberation of the ping off the target of interest. The acoustic pulse from an active source provides directional information (range and bearing) on a potential

submarine target more reliably than passive sonar systems. Additionally, when two or more active detections occur, it is possible to establish the speed and course of the submarine threat.

There exist many methods for eliminating a submarine once that threat is targeted. Traditionally, three methods for attack are airborne, standoff, and close attack. The most effective method is the airborne attack, as the submarine has little chance for a counter attack. The aircraft are able to traverse near the target submarine and drop lightweight torpedoes in very close proximity. The LCS can house and launch two MH-60R helicopters. These helicopters can carry a payload of three MK54 MAKO lightweight torpedoes. The MH-60R helicopters can fly on target, drop the MK54 torpedoes, and fly away while the torpedoes prosecute the submarine.

Platforms practicing ASW must also be able to survive an incoming attack so as to continue to provide ASW support for a battle group. Survival can be achieved through the use of evasion and countermeasures. Typically, when an LCS detects a submarine, the LCS will have its towed arrays deployed. The LCS is vulnerable while in this state, as it will be unable to evade any incoming attacks. The LCS can utilize decoy style counter-measures that try to soft-kill the incoming threat. A soft kill distracts the incoming threat until it loses fuel and is no longer a threat. The LCS equipped with the ASW mission package has the Light Weight Tow (LWT), which provides counter measure capability.

3. CONOPS of the Current LCS

The LCS is equipped to handle littoral ASW missions. According to the Department of the Navy (1998, "Mission and Tasks"), the missions for littoral ASW consist of the following:

> Sea Control Operations — Includes tasks required to gain adequate control of the seas in the U.S. maneuver area and thereby secure U.S. objectives in regional operations.

> Choke Point Operations — Includes tasks required to ensure choke points are maintained free of submarines that would deter or prevent the passage and freedom of navigation through any restrictive or strategically significant geographic location.

Submarine Mission Denial — Includes tasks required to prevent or hinder an enemy submarine from accomplishing assigned missions.

The open-ocean ASW mission consists of two sub-missions: Force Protection, and Operating Area Battlespace Dominance. Both missions include many of the same tasks as the mission associated with littoral ASW. Operating Area Battlespace Dominance includes Sea Control Operations, Choke Point Operations, and Submarine Mission Denial in a specified area of operations. Force Protection includes battlespace dominance, but has the added challenges of a moving area of operation. The radiated noise from the main force poses a challenge in this mission. The ships that form the main battlegroup are not designed with stealth as a priority, and can mask the sounds of a potential enemy. To overcome this, the LCS will utilize the "Sprint and Drift" technique described below.

A group of two to three LCSs will be deployed to the outer screen of the battlespace, approximately 12 to 25 nautical miles from the High Value Unit (HVU). The LCS will sprint ahead of the main battle group. This ensures that the noise of the main battle group does not interfere with the passive detection of possible submarine threats. Once the LCS establishes an adequate distance is itself and the HVU, the LCS will deploy its towed arrays and use its passive sensors. The LCS will do this while drifting, to eliminate as much self-radiated noise as possible.

The LCS can get on station very quickly and is able to deploy passive sonar as well as countermeasures. The biggest difference between open ocean and littoral ASW is the size of the area being searched and how long operations must take place before the LCS can restock supplies. The primary focus for proving LCS open-ocean ASW support will be to maximize the LCS's ability to stay on station, reduce the levels of self-radiated noise, and increase the range and accuracy of detections. As a HVU escort, the LCS can utilize other battle group assets for target elimination, and instead concentrate on detecting and targeting submarines.

The current 3500 nm range requirement for LCS (O'Rourke 2015a) is sufficient to support the these CONOPS.

D.   CURRENT SYSTEMS IN LCS ASW MISSION PACKAGE

The LCS currently utilizes three mission packages as illustrated in Figure 10: the surface warfare package, the mine-countermeasure package and the anti-submarine warfare package.

Mission packages are composed of mission modules, mission crew detachments and associated aircraft. The mission modules are broken down into mission systems and support equipment. The mission systems are further broken down into vehicles, sensors and weapons.

Figure 10. LCS Mission Packages
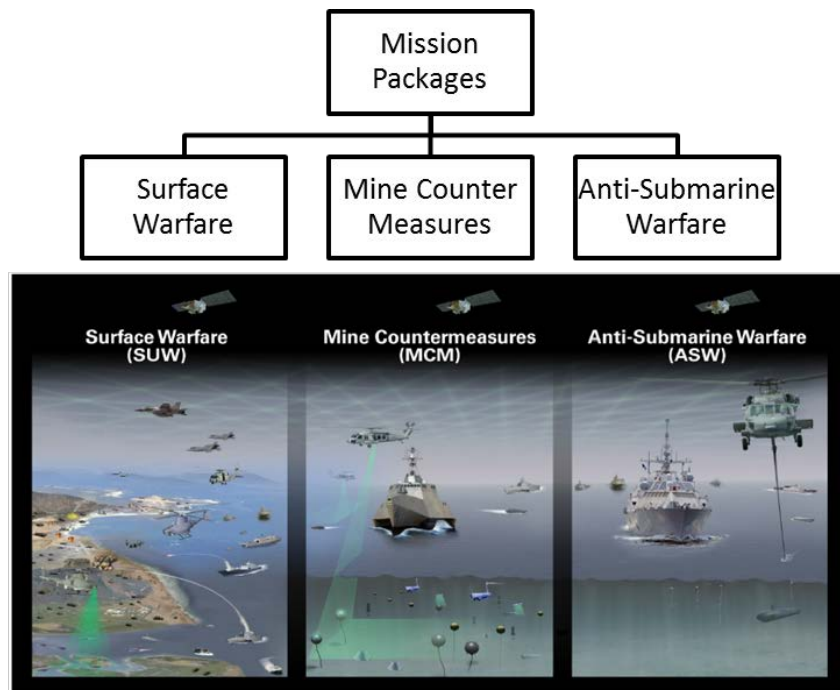
This report shall focus on the Anti-Submarine warfare mission package. The ASW mission package incorporates three mission modules: aviation, ASW escort, and ASW mission management/command & control. The aviation module is composed of an MH-60 helicopter with Airborne Low Frequency Sonar (ALFS), two Vertical Takeoff

Unmanned Aerial Vehicles (VTUAV) and support containers. The ASW escort module is composed of VDS, MFTA acoustic receiver, launch, handling and recovery equipment, signal processing and systems control, support containers, Torpedo Defense Module (TDM), and the LWT countermeasure system. The ASW mission management/command & control center is composed of the Mission Package Application Software (MPAS) and network interfaces with the total ship computing environment as part of the LCS sea frame. The MPAS consists of mission-specific application software that supports the mission packages in planning and execution.

The LCS ASW mission systems, consisting of both shipboard and aircraft based components, which are illustrated in Figure 11. The figure shows LCS deploying VDS, LWT, and the MFTA while airborne assets are depicted deploying sonobuoys and MK 54 torpedoes. The systems are technically mature; the U.S. Navy has fielded them separately in other programs. These are described in the following paragraphs.

Figure 11. ASW Mission

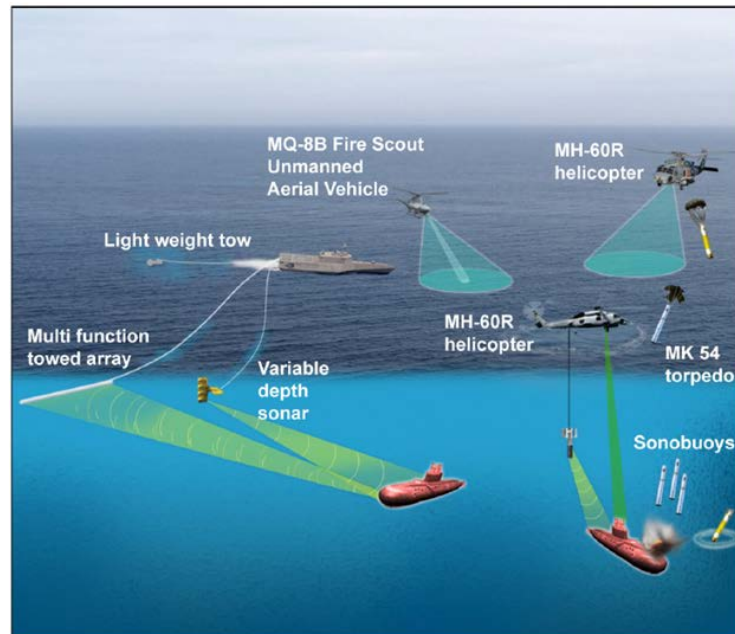Source: *Defense Industry Daily*, 2015, "LCS: The USA's Littoral Combat Ships," http:// http://www.defenseindustrydaily.com/the-usas-new-littoral-combat-ships-updated-01343/.

The VDS is a sound-producing active system capable of being deployed below the acoustic layer and provides an acoustic signal, which reflects back form target submarines. The MFTA is a towed array sonar system capable of transmitting and receiving acoustic signals, including the signal generated from the VDS. The MFTA and VDS are towed independently at the same or differing depths and capable of being deployed simultaneously at transit speeds. The LWT is a torpedo countermeasure, which is towed behind LCS. LWT transmits ship-like sounds to generate a false ship acoustic signature in order to divert torpedoes from LCS (Keller 2013). The MH-60R aircraft features Forward Looking Infrared Radar (FLIR), Laser Rangefinder/ Designator (LRD), Inverse Synthetic Aperture (ISAR), Airborne Low Frequency dipping Sonar (ALFS), sonobuoys, and MK54 Lightweight Hybrid Torpedoes (Lockheed Martin 2012). The MH-60R is an ASW multi-mission air platform capable of detecting, classifying and engaging target submarines. The Vertical Takeoff Unmanned Aerial Vehicle is the unmanned rotary wing aircraft, Fire Scout MQ-8B (Northrup Grumman 2015). This report does not include analysis of the Fire Scout, in order to limit scope to the LCS and the primary ASW aircraft used with it. The mission system is also comprised of launch and recovery equipment and handling equipment.

E.   ACOUSTIC MODEL

As noted previously, the LCS ASW Mission Package is equipped with a variety of sonar systems. These systems are the AQS-22 dipping sonar that the MH-60R uses to detect and target threats. The LCS itself employs VDS and MFTA towed arrays. These are advanced sonar systems, but as discussed earlier, the threats that the LCS must prosecute are continuing to grow quieter. As these ships become quieter, they will test the capabilities of the LCS sonar systems. The performance of the LCS' sonar systems were assessed through the development of an acoustic model. This model was generated by using a combination of sonar equations and publicly accessible information regarding the LCS threats, as well as the sonar systems being assessed. Specifically, the acoustic model's purpose is to determine the sonar-system's probability of detecting threats at a particular range.

The VDS is a towed array sonar system that can operate in active mode. Active sonar systems generate a signal to be reflected off a target. The system then listens for the reflected signal. The reflected signal will be transformed by the physical properties of the object it was reflected off of (Furuno Electric Co. 2016). In the case of an LCS prosecuting a threat, if the signal is strong enough, the reflected signal may contain properties of a submarine. This information, once processed at the sonar, can be used to determine if a threat exists, and if so, at what range and bearing (Federation of American Scientists 2016a). The AQS-22 is also a sonar system that operates in active mode. An MH-60R lowers this system beneath the surface of the ocean.

The MFTA is a towed array sonar system that operates in passive mode. The principles of passive sonar are similar to active sonar with the exception of the generated signal. Passive sonar does not generate a signal that reflects off the target. Passive sonar systems are constantly receiving signals (University of Rhode Island 2016). While this means that, in many cases, an active sonar system can detect a threat with higher reliability and at greater distances, a passive system does not produce a strong enough signal for a threat to detect. This allows for stealthier detection of targets.

To increase the chances of detecting a threat, it is desirable to have a high SNR (signal-to-noise ratio). Noise lowers the amount of *SE* (Signal Excess) that a sonar system receives (Wagner, Mylander and Thomas 1999). Signal Excess represents the amount of signal that exists at the receiving sonar system after that signal has been weakened by noises and spreading losses. These noises can come from many sources. These sources include, but are not limited to, the noise of the ship leveraging the sonar, the effect of weather conditions on the ocean, and traffic from other non-threat ships in the operating area (Wagner, Mylander and Thomas 1999). The total amount of signal loss due to these noises, as well as due to the distance that the signal must travel, is referred to as transmission loss (*TL*).

The sonar equations differ slightly between passive and active sonar. The effectiveness of the AQS-22 and VDS in active mode will be assessed using the active sonar equation, while the effectiveness of the MFTA will be assessed using the passive sonar equation. Detection Threshold (*DT*) is the amount of signal that must exist in order

to detect a target. Urick (1996, 17) states that, "When the target is just being detected, the signal-to-noise ratio equals the detection threshold." This provides the active sonar equation:

$$SL - 2TL + TS = NL - DI + DT \tag{1.1}$$

The left side of the equation describes the journey of the active signal. SL (Source Level) is the strength of the generated signal in decibels. It travels a distance through the ocean, weakening due to transmission loss (TL: Transmission Loss), is reflected and boosted by the sound generated by a target (TS: Target Strength), and returns to the sonar, all the while sustaining another round of transmission loss. The right side of the equation describes the sensing capabilities of the sonar-system (Urick 1996). Noise level, directivity index, and detection threshold are values unique to each sensor. Table 2 lists the different terms in the sonar equation, and what their value represents.

Table 2.   Sonar Equation Terms

Terms	Definition
SL	**Source level** radiated by the ensonifying sonar and measured at the ensonifying sonar.
TS	**Target Strength**, a measure of sound reflected by a target.
NL	**Noise level**, a measure of self and ambient noises.
DT	**Detection threshold**, the SNR required for detection.
SNR	**Signal to noise ratio**
SE	**Signal excess**, the difference between provided SNR and SNR required for detection
TL	**Transmission Loss**, loss of signal strength from target to sonar due to ambient noises.
FOM	**Figure of Merit**, value representing performance of the sonar. This value indicates "the maximum transmission loss the system can have and still be able to detect the target (at 50% of the time)" (Federation of American Scientists 2016b)

The *FOM* of each sonar system to each target must be calculated in order to determine probability of detection. Fortunately, the active sonar equation provides us with enough information to calculate the FOM:

$$FOM = (SL + TS) - (NL - DI) - DT \qquad (1.2)$$

This report's "Threat Analysis" section identifies each threat's source level, in decibels. Urick provides a value of 25 dB as target strength for a loud submarine. One calculates FOM using the target strength values, as well as the properties of the VDS. The terms used in VDS calculations are provide in Table 3. Table 4 describes the values used within the acoustic model for VDS against each threat.

Table 3.   Variable Depth Sonar Properties

Term	Value(dB)	Reference
NL	82	**Noise Level** *derived from (Urick, Principles of Underwater Sound 1996, 210)*
SL	221	**Source Level** *derived from nominal values contained within (Urick, Principles of Underwater Sound 1996, 412)*
DI	0	**Directivity Index** *is 0 as omni-directional is assumed.*
DT	25	**Detection Threshold** *derived from nominal values contained within (Urick, Principles of Underwater Sound 1996, 395)*

Table 4.   Variable Depth Sonar Figure of Merit against LCS Threats

Target	Source Level (dB)	Target Strength (dB)	*FOM* (dB)
Type 095	100	25	139
Yasen	100	25	139
Shang	110	25	139
Akula	110	25	139
Lada	110	25	139
Sinpo	120	25	139
Kilo	120	25	139
Song	120	25	139
Yuan	120	25	139
Sang-O	130	25	139
Romeo	150	25	139

Source levels of each submarine were determined by using known values for the Romeo and Akula (O'Rourke 2015b) classes, and assuming a gradual decrease in sound profile based upon years commissioned, and advances in sound dampening technology.

Information regarding target strength of each class of threat is not readily available. Urick assumes a value of 25 dB as a target strength for submarine, and this report will make the same assumption. As a result, instead of calculating the VDS performance for each threat, one will assess an approximate, "overall" performance of the VDS. This probability of detection must be calculated in order to determine the true effectiveness of the sonar-system. In order to calculate probability of detection, the formula for determining spherical spreading transmission loss will be used. Spherical spreading is assumed as this is typical of open-ocean environments.

$$2TL = 20\log(R) \qquad\qquad (1.3)$$

In Equation (1.3), *R* represents the range of the sonar to the target in yards. This value is unknown, but it can be determined by rewriting the formula using the active sonar equation to substitute values for *TL*:

$$R = 10^{\frac{FOM - SE}{40}} \tag{1.4}$$

Equation (1.4) provides the ability to calculate a target's range given the *FOM* and *SE*. For a 50 percent chance of detecting a target, *SE* must be equal to 0 dB. Using Figure 12, it can be approximated that for every 1 dB change in *SE*, probability of detection increases or decreases by 5 percent for *PD* (Probability of Detection) between 10 percent and 90 percent.

Figure 12. Probability of Detection vs. Signal Excess
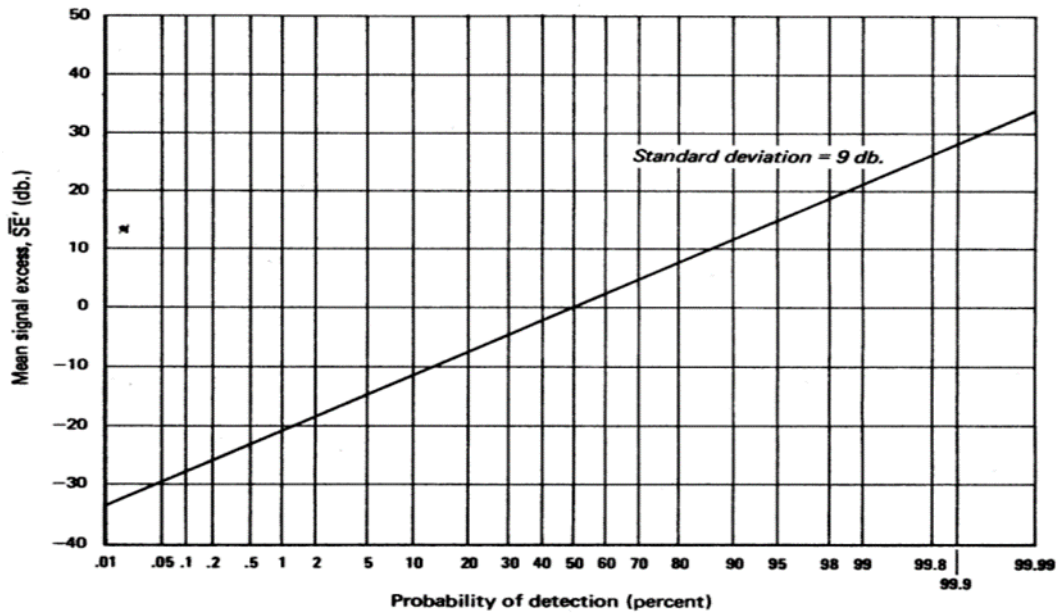
Source: William J. Hurley, 1980, *An Introduction to the Analysis of Underwater Acoustic Detection*, Arlington, VA: Center for Naval Analyses.

Using Figure 12 to map *SE* levels to probability of detection, and using Equation (1.4) to determine range, PD between 10 percent and 90 percent can be calculated of the VDS against a target at certain ranges. Figure 13 displays the results of these calculations.

Figure 13. Acoustic Model Derived Probability of Detection vs. Range for VDS against Threats
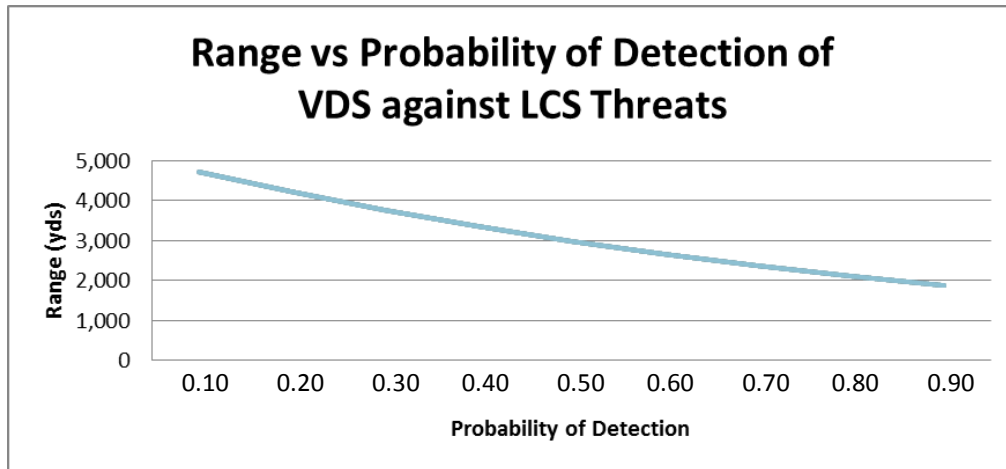
At 2 kyds, VDS has the capability of detecting threats identified with a 90% probability. At further distances, the probability of detection decreases towards 10% nearing 5 kyds.

PD at range can be calculated for the AQS-22 using the same equations, as AQS-22 is an active sonar-system. Figure 14 provides the results of these calculations. While the properties of the threats will remain the same in AQS-22 calculations, the properties of the sonar-system will differ, and are described in Table 5.

Table 5.   AQS-22 Sonar Properties

Term	Value (dB)	Reference
NL	50	**Noise Level**, *derived from (Urick, Principles of Underwater Sound 1996, 210)*
SL	217	**Source Level** *derived (NOAA 2008)*
DI	0	**Directivity Index** *derived from (Urick, Principles of Underwater Sound 1996, 412)*
DT	25	**Detection Threshold** *derived from nominal values contained within (Urick, Principles of Underwater Sound 1996, 412)*

Figure 14. AQS-22 against LCS Threats
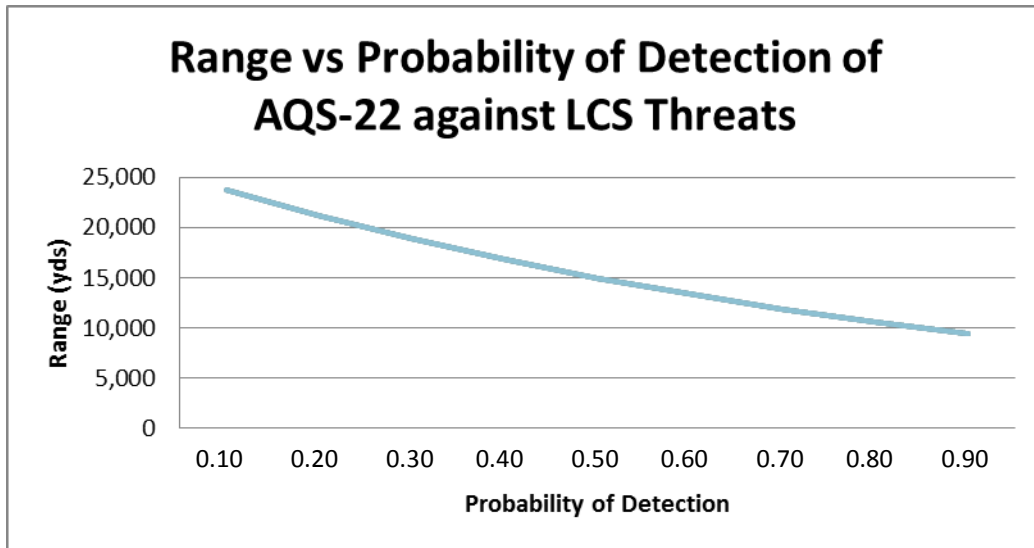
Figure 15 shows that the ranges in which the AQS-22 can detect threats are significantly greater than that of the VDS.

Figure 15. AQS-22 vs. VDS Probability of Detection against Range
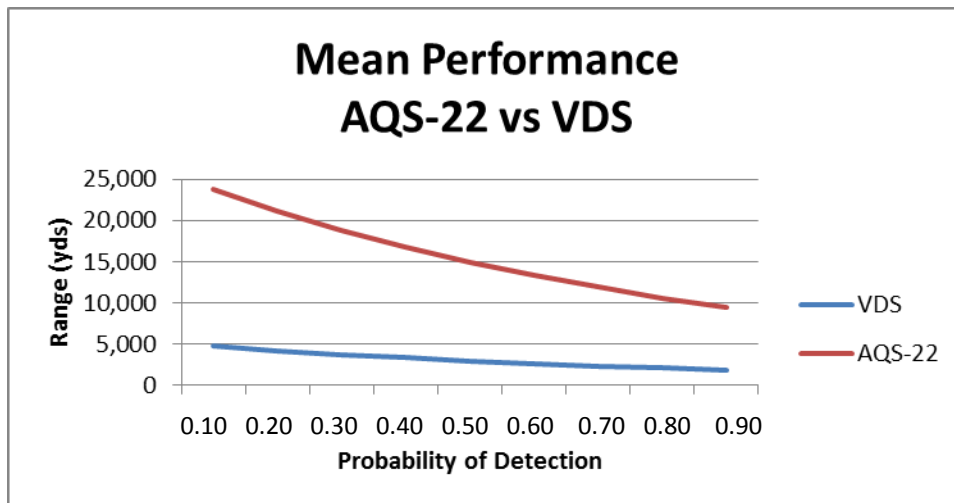
While the VDS appears to be a better sonar based upon its greater *SL*, the AQS-22 has the advantage of a much lower *NL* due to it not being in close proximity to its platform host. When *NL* is assumed to be equal for both sonar-systems, as demonstrated in Figure 16, VDS would rate as the more effective sonar, but not by a significant margin.

Figure 16. AQS-22 vs. VDS Probability of Detection against Range Assuming Equal NL
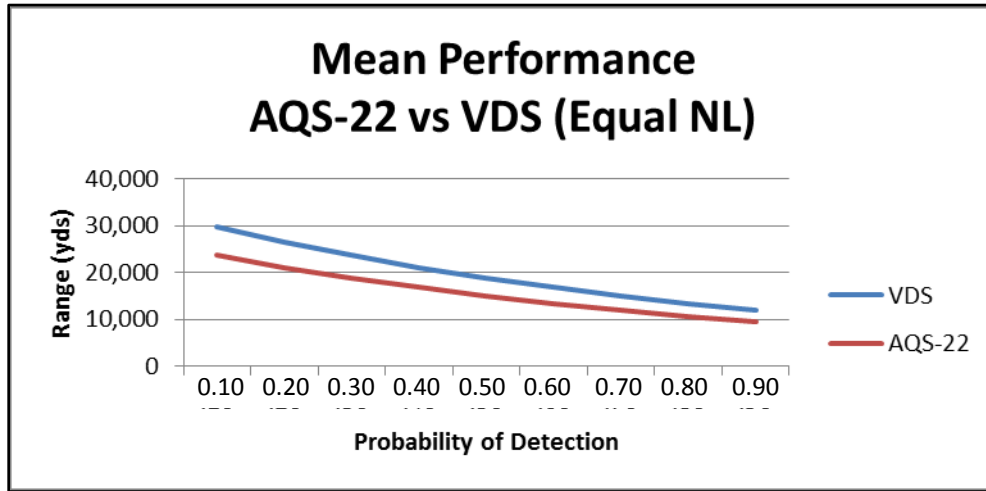
The MFTA passive sonar-system's *PD* versus range against LCS threats must be calculated differently than VDS and AQS-22. Passive sonar-systems must use the passive sonar equation:

$$SE = SL - TL - NL + DI - DT \qquad (1.5)$$

This sonar equation is similar to the active sonar equation, but it has two key differences. There exists only one-way transmission loss of the signal in the passive equation, and *SL* refers to the radiated noise produced by the target submarine, and not the signal transmitted by the host platform's sonar. In this equation, *NL* represents not only the self-noise levels of the sonar-system and host platform, but also the transmission loss due to ambient noises of the ocean. Additionally, the equation to determine range to

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target must also change in order to reflect one-way transmission loss instead of the two-way transmission loss observed in the active equation:

$$R = 10^{\frac{FOM - SE}{20}} \qquad (1.6)$$

Using Figure 12 to map *SE* levels to probability of detection, Equation (1.6) to determine range, and MFTA values as provided in Table 6, *PD* between 10 percent and 90 percent can be calculated of the MFTA against a target at certain ranges. Calculating these values yield the results seen in Figure 17.

Table 6.   MFTA Sonar Properties

| Term	Value (dB)	Reference
NL	82	**Noise Level** *derived from nominal values contained within (Urick, Principles of Underwater Sound 1996, 412)*
DI	0	**Directivity Index** *derived from nominal values contained within (Urick, Principles of Underwater Sound 1996, 412)*
DT	8	**Detection Threshold** *derived from nominal values contained within (Urick, Principles of Underwater Sound 1996, 413)*

Figure 17. MFTA Probability of Detection vs. Range against LCS Threats
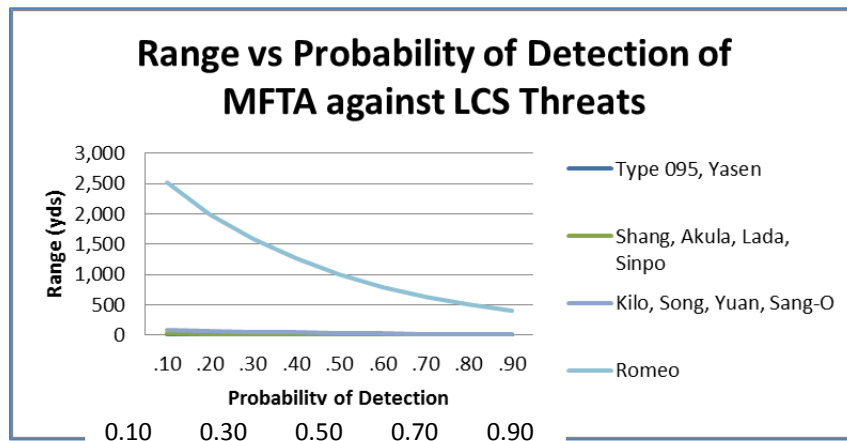
The MFTA is capable of detecting the Romeo class submarine at very far distances, much further than the active sonar. This is most likely a result of the Romeo class being a very noisy threat, and not indicative of the MFTA's performance. This outlier skews the range into the millions of yards. Removing the Romeo from the calculations, as demonstrated in Figure 18, provides a more useful model. Overall performance of the systems is shown in Figure 19.

Figure 18. MFTA Probability of Detection vs. Range against LCS Threats (Romeo removed)

Figure 19. LCS Sonar Performance Comparison
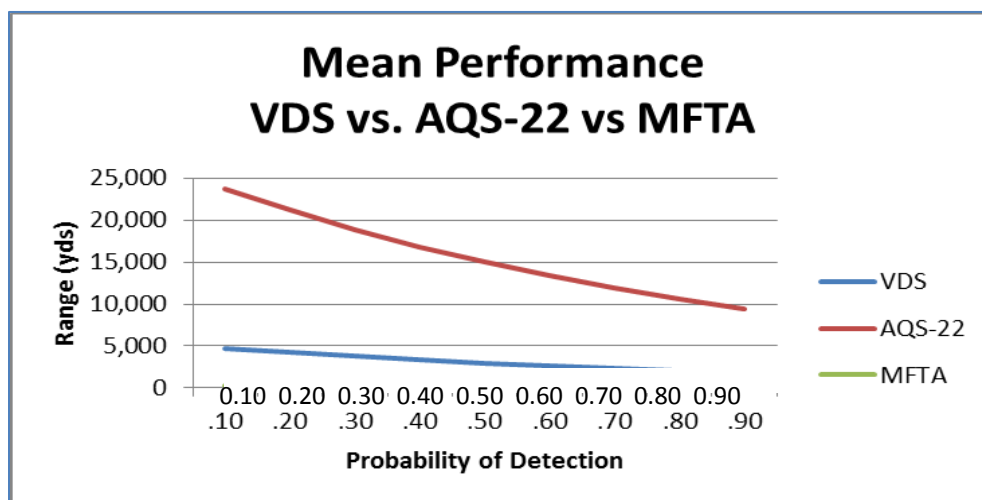
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III. CURRENT CAPABILITY GAPS

The previous chapter presented the ASW mission analysis as it relates to LCS. Based on that evaluation, the following requirements were generated to characterize the LCS as a viable open-ocean ASW platform:

1. LCS shall have a range of at least 3500 nm at a cruise speed of 14 knots.
2. LCS shall maintain hangar capacity to store two ASW-capable helicopters.
3. LCS crew shall be trained to support a multi-LCS ASW CONOPS.
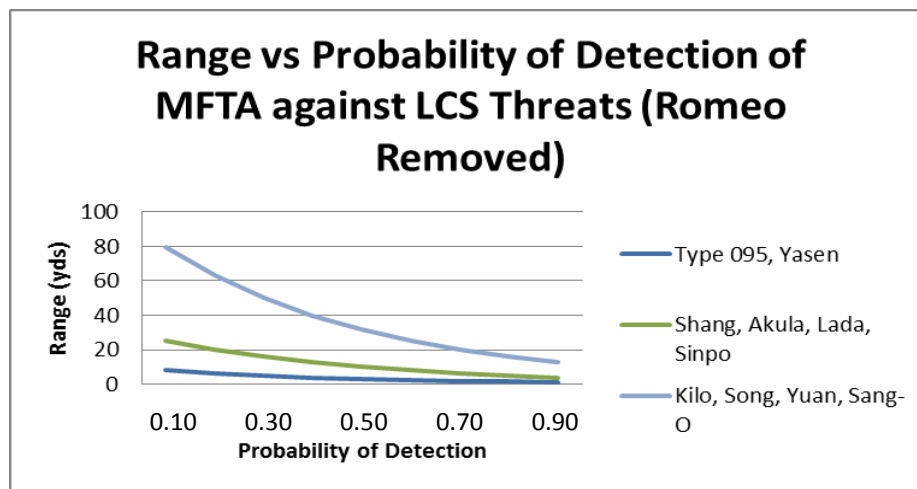4. LCS shall be interoperable with other ASW platforms.
5. LCS shall maintain a ship-silencing program.

Comparing the current LCS capabilities to the capabilities needed for open-ocean ASW stated above, three primary capability gaps were identified which significantly affect the LCS's suitability to adequately perform open-ocean ASW. Analysis of the first gap, Ownship Noise Control Capability, led to a sixth requirement that will be discussed in Chapter IV.

A. OWNSHIP NOISE CONTROL CAPABILITY

The first capability gap discussed is ownship noise control. Awareness of ownship radiated noise and control of it are critical elements of the ASW mission. The range at which an enemy threat is capable of acoustically detecting and classifying ownship is a function of the magnitude of ownship radiated noise. Therefore, ownship detectability and vulnerability ranges are defined by radiated noise. A decrease in ownship radiated noise can directly decrease the range at which the threat can passively detect, track and classify ownship (Urick 1996).

The LCS's acoustic silencing control systems must be addressed for the LCS to adequately fulfill the open-ocean ASW mission. This gap is understandable since LCSs were designed to operate in noisy environments where ownship noise control was not a concern. When LCSs were constructed, no effort was dedicated toward acoustic silencing control (ComNavOps 2013). Now that LCS will be preforming open-ocean ASW missions, ownship noise control should be a primary objective.

B. RANGE AND ENDURANCE CAPABILITY

Another capability gap identified was limited range and endurance of the LCS. As weight of a ship increases, the endurance and speed of the ship decreases (Stavridis and Girrier 2006). Certain speed and endurance performance objectives are required to perform the sprint and drift CONOPS discussed in this report. According to a Congressional Research Service report, the LCS's operating range is estimated at 1961 nautical miles at 14 knots well below the 3500 nautical mile U.S. Navy requirement (O'Rourke 2015a). Furthermore, at 110 metric tons, the LCS ASW mission module currently surpasses the 105 metric ton design limit by 5 metric tons (O' Rourke 2015a). The weight of LCS hinders her ability to meet speed and endurance requirements, which ultimately affects the ASW effectiveness.

C. DATA LINK CAPABILITY

The lack of a high capacity data link limits the communication capability between ships and aircraft and represents a gap for LCS. The MH-60R aircraft is capable of detecting and prosecuting enemy submarines. However, the aircraft cannot detect and prosecute in a single sortie. The aircraft cannot process sensor data it collects to be able to prosecute a submarine if detected while in flight. The sensor data must be passed to the LCS to be processed, and this requires that the aircraft land and the data downloaded by a physical connection. The MH-60R aircraft can utilize both Link 16 and the Ku-band Tactical Common Data Link (TCDL) Hawklink System (Lockheed Martin 2011) when communicating with LCS. Each of those communication systems have different benefits. One benefit of Link 16 is that it has been widely deployed, permitting communications with many types of platforms, including ships, aircraft, space assets, and ground forces. Link 16 is a relatively low bandwidth, frequency-hopping, jam-resistance data link, which requires processing of acoustic data to be performed on the aircraft (Northrup Grumman 2014). Link 16 is capable of passing tracks, locations, and other post-processed data outputs, but it does not have sufficient bandwidth to support passing bulk sensor data before it is processed (Northrup Grumman 2014). In contrast, the Ku-band TCDL is capable of passing bulk sensor data to other platforms for processing, thereby

allowing operators to be located shipboard (Nilsen 2011). LCS is only able to support Link 16 and is unable to utilize the higher bandwidth Ku-band TCDL.

The previous chapter identified current LCS ASW capability gaps. The next chapter identifies potential improvements for each of the capability gaps. Additionally, the following chapter provides potential improvements to LCS ASW CONOPS.

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IV. POTENTIAL LCS IMPROVEMENTS

Once capability gaps were identified, the team evaluated various systems that could be potential solutions to fix the gaps. The recommendations in this report should improve the LCS's ability to accomplish open-ocean ASW.

A. ACOUSTIC CONTROL IMPROVEMENTS

Because ownship's noise is a limiting factor in ASW operations, there is an inherent need to reduce the LCS radiated noise signature. For the purpose of this report, the LCS source level was assumed to be 157 dB (Table 7) which corresponds with that of a corvette; a similar sized ship (Urick 1996). To be viable in the ASW role, the LCS must be able to achieve and maintain an acoustic advantage over threat submarines. Therefore, a nominal acoustic threshold of 140 dB was selected as a goal based on the results of Figure 23 and becomes the sixth requirement previously mentioned, with the understanding that further investigation is required to identify actual operational acoustic requirements. To achieve this requirement and to reduce the radiated noise of the LCS, the following acoustic controls need to be addressed: noise reduction around the hull of the ship, noise reduction associated with propulsion, internal sound isolation, and ownship radiated noise awareness.

U.S. Navy destroyers (DDG) and cruisers (CG) that conduct open-ocean ASW are outfitted with radiated noise reduction systems, specifically Propeller Air Internal Emission (PRAIRIE) and Masker Air systems (Saunders 2002). Both PRAIRIE and Masker systems are designed to reduce inherent radiated noise signature of the ship, thereby making detection of the ship difficult. By utilizing these systems appropriately, they provide a significant acoustic advantage during ASW operations.

As depicted in Figure 20, the Masker Air system uses a series of belts that wrap around the hull of the ship beneath the waterline. Small holes are drilled through the entire length of each belt where diverted exhaust air is allowed to leak out and form bubbles. The bubbles create a blanket of bubbles around the ship's hull when the ship is in motion and works as a noise attenuator (Surface Officer Warfare School 2002).

Masker is effective at reducing shipboard machinery noise that radiates into the environment. An alternative to the Masker Air system are acoustic tiles, which provide similar radiated noise reduction benefits (Global Security 2011).

Figure 20. Master Air System as Shown on Ship's Hull
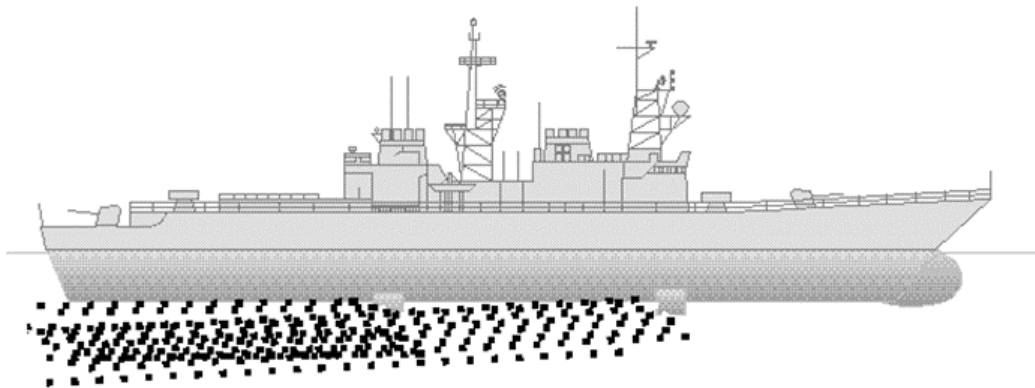
Source: Surface Officer Warfare School, "Ship's Silencing Program," Information Sheet Number 9.7, Newport, RI: Surface Officer Warfare School.

The PRAIRIE air system uses the same exhaust air as the Masker system but implements it differently. PRAIRIE air reduces the noise generated by propeller cavitation. To that end, PRAIRIE air is distributed along the port and starboard propeller blade tips as seen in Figure 21 (Surface Officer Warfare School 2002). Bubbles released from the blade tips fill the void left by rotating blades as the water boils. This allows the cavitation bubbles to contract slower as the area of under pressure is minimized (Surface Officer Warfare School 2002). The resulting effect from this process is a significant reduction in propeller cavitation noise.
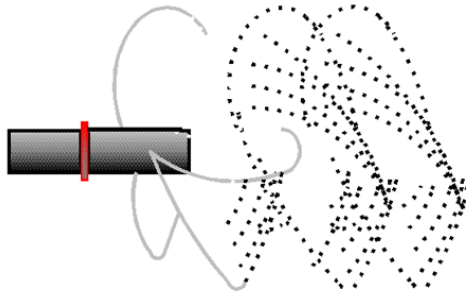
Figure 21. PRAIRIE Air System in Use on Propeller of Ship

Source: Surface Officer Warfare School, "Ship's Silencing Program," Information Sheet Number 9.7, Newport, RI: Surface Officer Warfare School.

Although the LCS has a water-jet propulsion system, further researchers should identify ways to reduce the LCS's propulsion noise. Systems like the PRAIRIE and Masker air systems could be implemented on the LCS. Masker air belts could be placed on the hull of the LCS reducing the noise radiated to the environment. A system similar to the PRAIRIE air could also be implemented with the water jets on the LCS. A bubble blanket that surrounds the wake of the water jets may reduce the noise radiated to the environment.

Another technique to reduce ownship noise would be sound isolation control using resilient machinery mounts throughout the LCS. Sound isolation mounts are designed to dampen or eliminate vibrations transmitted to the hull and thus into the water. The current LCS design does not have any of the noise reduction or control features (ComNavOps 2013). Sound isolation controls would further reduce ownship noise and improve the effectiveness of the open-ocean ASW mission.

Ship operating procedures can also be developed to reinforce acoustic silencing posture. A ship silencing instruction can be developed which is hull-specific and used during ASW operations when ownship noise is required to be at a minimum. The ship silencing instruction is a document that records the quietest configuration of the ship, describing what machinery should and should not be energized, along with the ship's most recent radiated noise information. To gather this information accurately, a periodic radiated noise signature evaluation of the ship would be required. The hull-specific

radiated noise signatures and acoustic related feedback can be used for mission planning and future improvements. Using this data, ships can model their counter-detection ranges based on the suspected threat and their operational area. This proves to be an invaluable tool when conducting sustained ASW mission operations.

The potential acoustic signature improvement areas can be further described in terms of probability of detection and counter-detection. For the purposes of this comparison, an acoustic improvement of 25 dB was considered. To account for the acoustic improvement with respect to the mean performance of the MFTA, the values in Table 6 were utilized and the following noise reduction values were applied to the Noise Level (NL) parameter: -5 dB internal sound isolation, -10 dB noise reduction around the hull, -10 dB noise reduction associated with propulsion cavitation. Figure 22 shows the probability of detection of the relative acoustic noise reduction of the LCS platform with any combination of acoustic signature improvements.

Figure 22. Mean Performance of MFTA with Potential Acoustic Improvements

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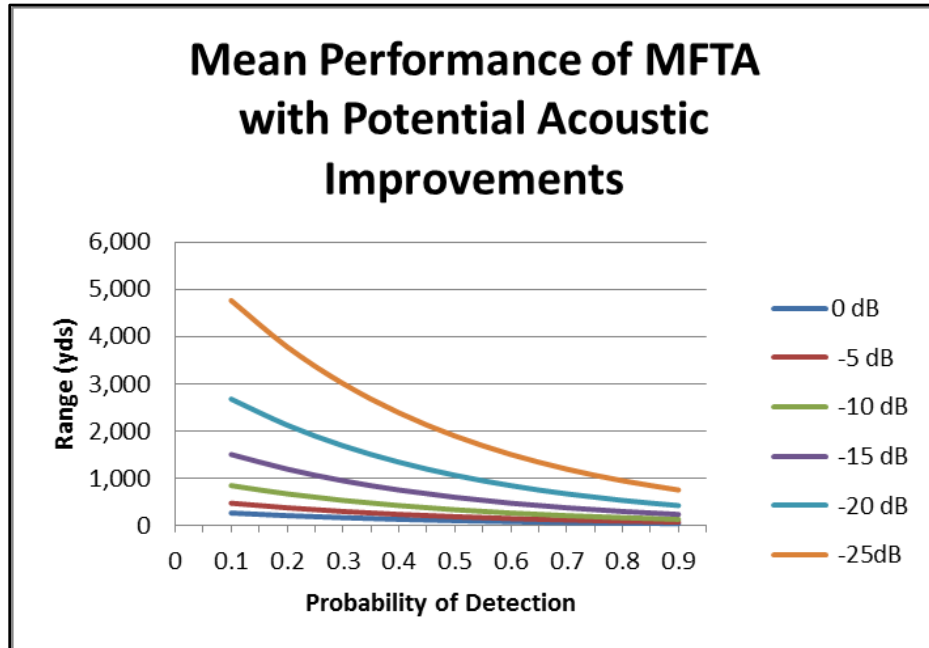
The model shows that as more acoustic silencing features are applied to the LCS, the probability of detecting a submarine that is a threat increases. Similarly, these features also affect counter-detection of the LCS. Equations 1.5 and 1.6 were utilized to generate counter-detection ranges and the input parameters are provided in Table 7.

Table 7.   Counter-Detection Parameters

	Term	Value (dB)	Reference
Threat Submarine	*NL*	105	**Noise Level** *derived from nominal values contained within (Urick, Principles of Underwater Sound 1996, 375)*
	DI	20	**Directivity Index** *derived from nominal values contained within (Urick, Principles of Underwater Sound 1996, 375)*
	DT	8	**Detection Threshold** *derived from nominal values contained within (Urick, Principles of Underwater Sound 1996, 413)*
LCS	*SL*	157	**Source Level** *derived from nominal value of corvette sized ship contained within (Urick, Principles of Underwater Sound 1996, 346)*

In a similar fashion, a 25 dB acoustic improvement was applied to the LCS source level. The counter-detection results are provided in Figure 23, which shows the 50 percent probability of counter-detection of the LCS from a threat submarine. When the LCS's radiated noise is reduced with the aid of acoustic silencing features, the corresponding counter-detection range also decreases. Due to the complexity of these features and the lack of historical data to reference, cost estimations associated with these acoustic features could not be generated. Further research is required to provide an adequate cost-benefit analysis.

Figure 23. Counter-Detection Reduction
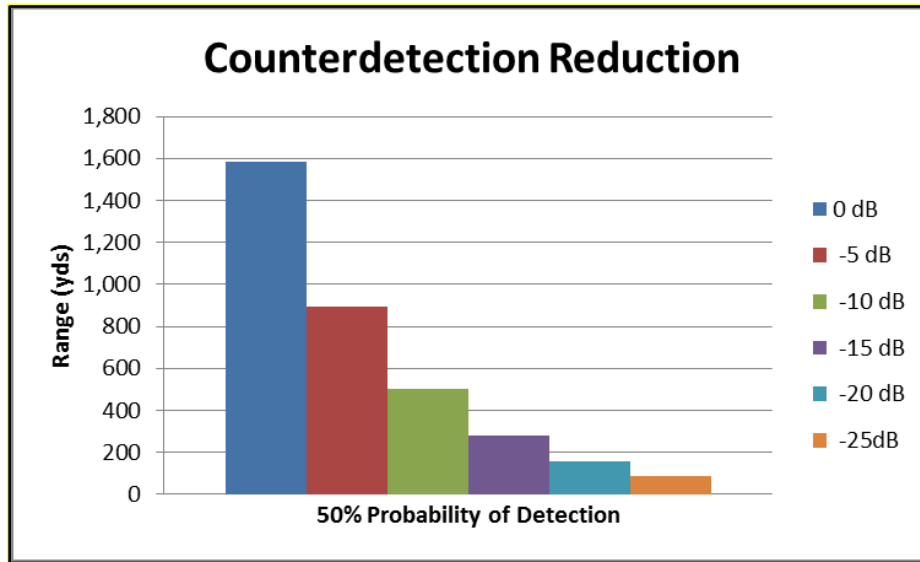
B.   POTENTIAL CONOPS IMPROVEMENTS

The LCS has been designed to tranist operating areas quickly and can deploy passive sonar and countermeasure systems. Differences between open ocean and littoral ASW are the size of the area being covered and the duration of operations on station. The focus of open-ocean ASW shall be to maximize the LCS's on-station time, reduce the levels of self-noise and increase the range of detections. As part of the battlegroup, LCSs can concentrate on detecting and classifing submarines and other platforms in the battlegroup can neutralize the enemy submarine. Other differences are how the various sensor systems respond to the different environments. In littoral water, convergence zone detections are impossible and classification is difficult because of the higher noise levels and environmental noise in shallow water.

Utilizing three LCSs together can employ a combination of active and passive sonar techniques to take advantage of multistatic signal processing. Multistatic signal processing employs multiple signal sources and receivers that are spatially separated. Passive and Active Multistatic Search (PAMS) uses three LCSs to create a multistatic acoustic system. While one LCS sprints to the next position, it actively pings through the deployment of its helicopters, searching for any enemy submarines in the area.

Simultaneously, the other two LCSs are drifting with their towed arrays deployed using their passive sonar systems. Figure 24 illustrates the phases of the PAMS cycle, and positions of the three LCSs. In phase one, the port-to-starboard crossover, LCS 1 sprints forward while the other two are drifting. Once LCS 1 surpasses LCS 2 along the threat axis, it throttles down to a drift and begins deploying passive sensors. In phase two, the starboard-to-port crossover, LCS 2 retrieves its passive sensors then begins to sprint ahead. Once LCS 2 surpasses LCS 3 along the threat axis, the cycle repeats with LCS 3 retrieving sensors and sprinting ahead in a port-to-starboard crossover.

Figure 24. Passive and Active Multistatic Search Cycle Using Three LCS

Cycle Phase 1: Port-to-Starboard Crossover   Cycle Phase 2: Starboard-to-Port Crossover
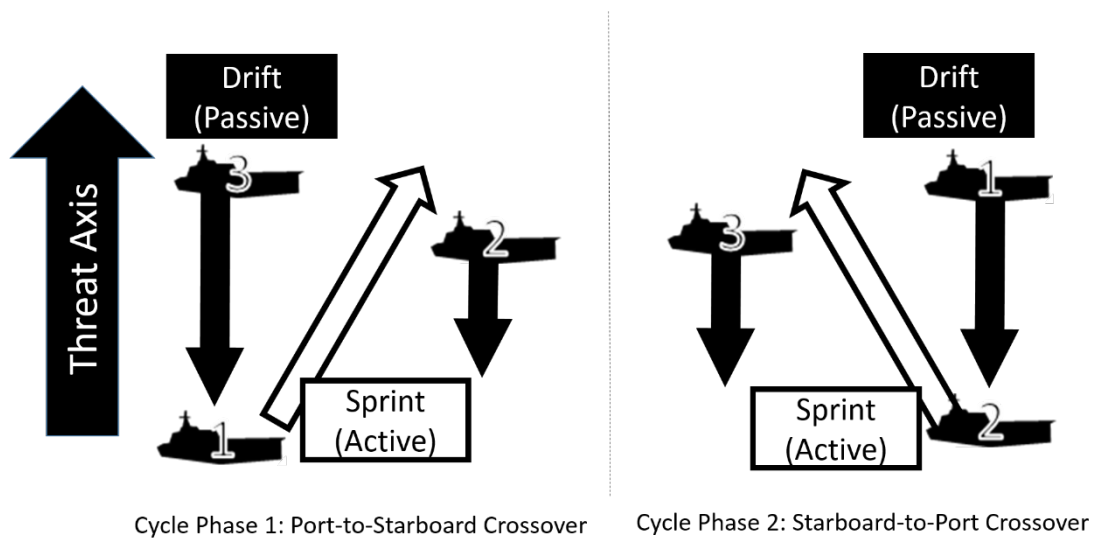
Passive and Active Multistatic Search (PAMS) maximizes the mission denial capability of the LCS. Active sonar can target a sumbarine in as little as two pings. However, using active sonar can be innefectve, since possible target can detect and avoid detection. As described in Figure 25, a submarine detects the active pings roughly twice the distance than an LCS can receive an echo from an active transmission based on the sonar equation.

Figure 25.   Maximum Beaconing Range Vs Maximum Detection Range

Max Beaconing Range for LCS   Max Detection Range for LCS
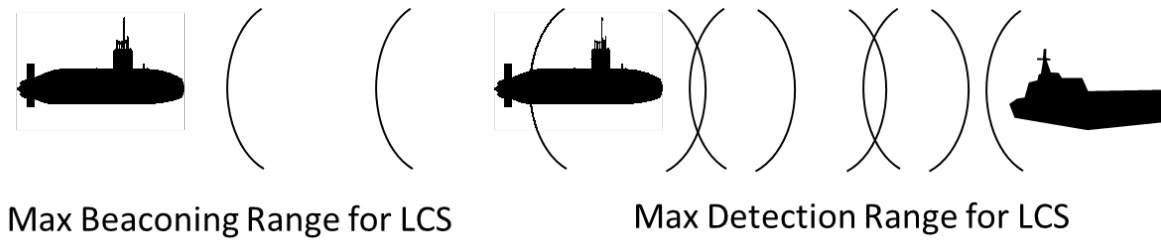
The enemy submarine can determine by beaconing the location of the LCS and choose to evade detection or even engage the LCS. If the submarine evades then ultimately the HVU are safe. If the enemy submarine chooses to engage, the enemy sub can close half the distance to the LCS before the LCS can even detect the submarine. Using the PAMS techniques an undetected LCS may be able to corner an enemy sub avoiding an actively pinging LCS. Figure 26 illustrates how LCSs, using passive sonar sensors, overlap the area where a beaconed submarine considers safe to operate in.

Figure 26. PAMS Detection Overlays
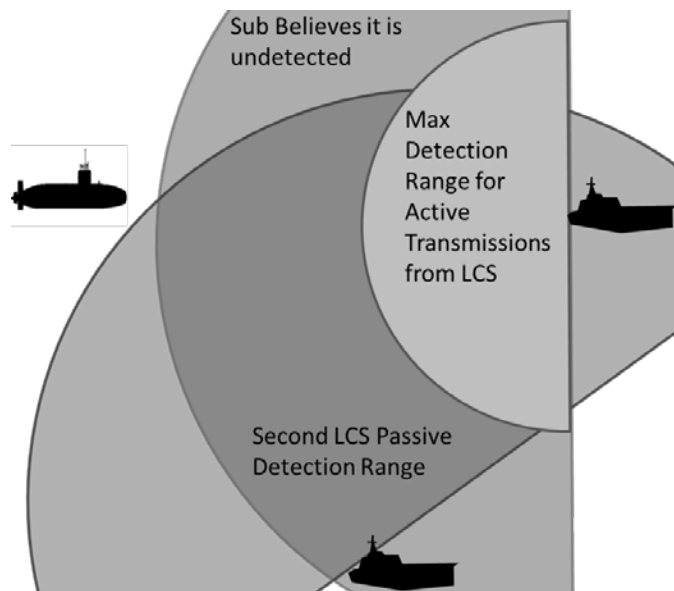
By continually overlapping the passive detetction area with the active transmissions area, a team of three LCSs can effectively create a submarine denial area. Employing several teams around the HVU, the entire battlegroup can be shielded from the possible entry of a submarine into an operating area. In order for the PAMS techique to be successful, the self-noise level of the LCS must be low enough or quiet enough that an enemy sub would have difficulty detecting it.

C.   RANGE AND ENDURANCE IMPROVEMENTS

To perform open-ocean ASW missions effectively, the LCS needs to have greater range and endurance. Open-ocean ASW missions take place over a much greater operating area and do not always have refueling sources available, an LCS will need to be capable of staying on station for longer and travel great distances. Both capabilities can be simplified to fuel consumption of the LCS. The less fuel consumed, the longer the LCS can be on mission.

There are two proposed methods for decreasing fuel consumption. The first method is to substantially lower the weight of the LCS ASW mission package. The reduction in weight of the ASW mission package should be dedicated to expanding the amount of fuel stored on the LCS. The other method is to change the operating mode of the LCS while in transit to decrease fuel consumption.

Weight is a major factor in calculating displacement, which is a factor in calculating drag and fuel consumption during transit. Weight has a direct relationship with fuel consumption; a 1 percent decrease in weight results in a 1 percent increase with fuel efficiency. This relationship is in part the basis for "[t]he Navy is soliciting industry for suggestions to reduce the package's weight by at least 15 percent" (O' Rourke 2015a, 33). The Navy is contracting Advanced Acoustic Concepts, L-3 Communications, and Raytheon to perform transition studies to reduce the weight. These results are still ongoing and not published, but all three proposals will reduce the ASW mission package below the 105 metric ton limit.

For this report, the team investigated the improvements to range and endurance of the LCS by removing the VDS system from the mission package. While the VDS system

is very useful at local submarine detection, the team's analysis shows that the most effective detection method is from the two ASQ-22 equipped helicopters. The VDS is most effective at close ranges making it less useful for open-ocean ASW. The VDS weighs 34.7 metric tons. By removing VDS, the ASW mission module would weight 34.7 metric tons less, well below the 105 metric ton limit. The removal of VDS would also reduce the entire displacement of the LCS by approximately 1 percent. This 1 percent reduction in displacement equates to a one percent reduction in fuel consumption.

Figure 27 shows the difference in fuel consumption of the LCS with and without the VDS system onboard and shows that a 1 percent decrease in total displacement has almost no real impact on fuel consumption.

Figure 27. Displacement Effect on Fuel Consumption
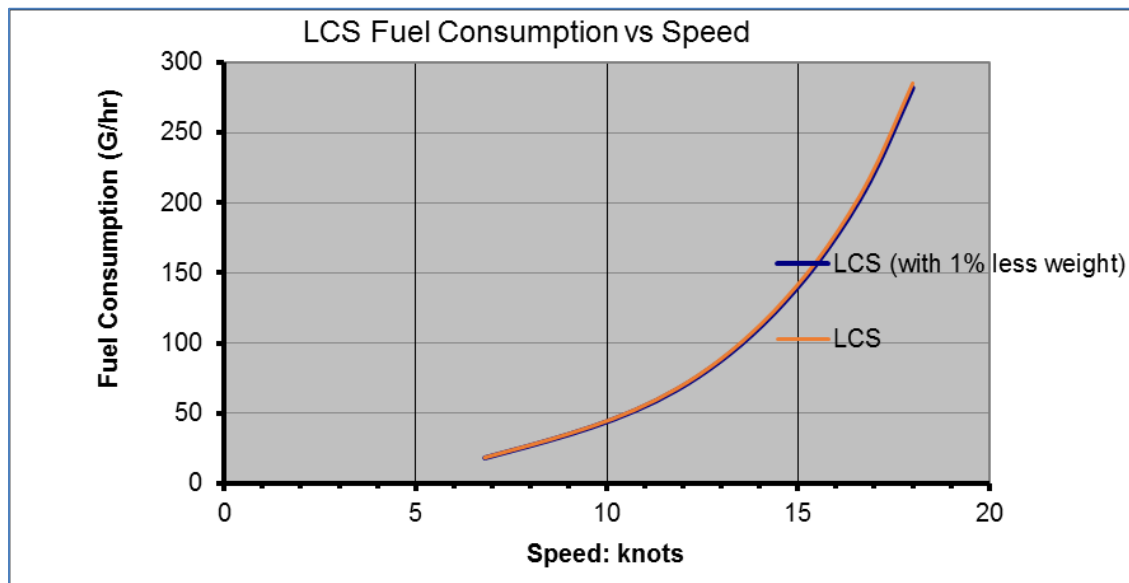
A 1 percent reduction in displacement does not have a significant impact on fuel consumption rates.

If the removal of VDS was replaced by extra fuel reserves, the LCS could greatly expand its onboard fuel. According to the Environmental Protection Agency (EPA), diesel fuel weighs 7.37 pounds per gallon. Dividing the 34.7 metric tons saved by removing the VDS by 7.37 pounds per gallon results in 10380 gallons of fuel that could

be added to the LCS with no change in the total weight. This extra fuel equates to approximately a 10 percent increase in fuel storage. Figure 28 shows that a 10 percent increase in fuel storage will have about a 10 percent increase in overall range.

Figure 28. Fuel Storage Effect on Range
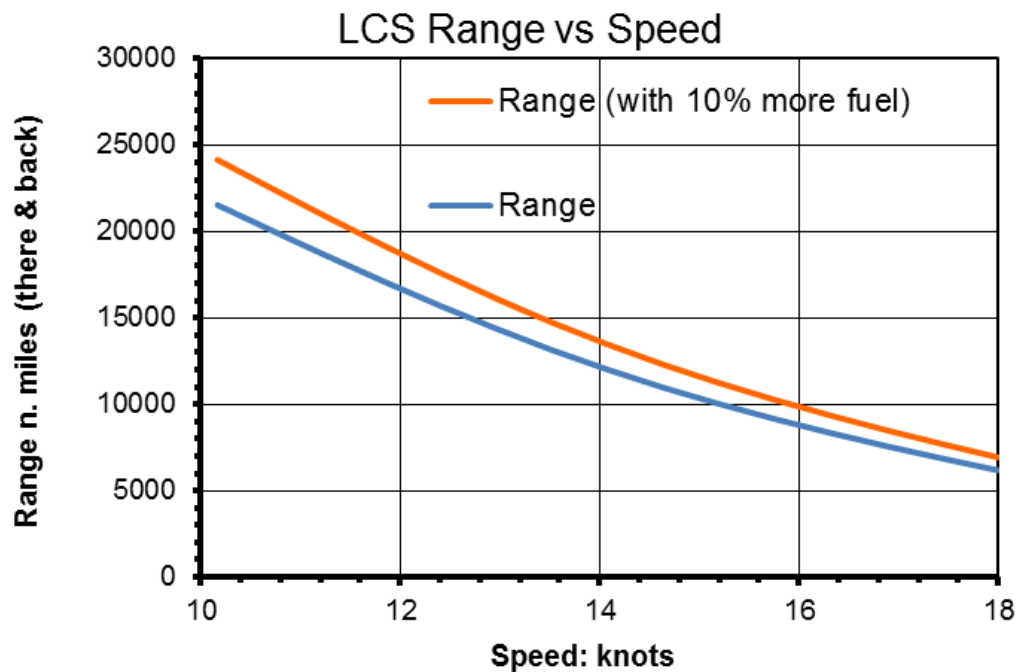
Exchanging the VDS for an equal wright of extra fuel improves range by an average of 10 percent.

The models for range and fuel consumption versus speed are based on twin propeller propulsion calculations developed by boatdesign.net. The LCS uses a water jet instead of the twin propeller used for the calculations, yet the effects on fuel consumption and range remain the same (Michael 2003). However, Michael states that the change in fuel consumption due to displacement and the impact of extra fuel storage on range are both representative of a waterjet propulsion hull.

Another factor in fuel consumption is the control of the throttle while in transit (Burpa 2012). Burpa's thesis explores the effects of mixed mode travel speed during transit to optimize fuel consumption. His thesis specifically looks at the LCS hull USS

Freedom (LCS-1), analyzing various potential missions in a Western Pacific deployment. Burpa's thesis used the mixed-mode minimization planner, developed by NPS professors, with optimization tools to calculate combinations of throttle speeds throughout a transit leg. Burpa concluded that with the mixed-mode transit, LCS "will see fuel consumption savings ranging from three to 12 percent" (Burpa 2012, 65).

Calculating the mission effectiveness achieved by implementing mixed-mode transit is rather straightforward. Mixed-mode transit can reduce the performance gap by up to 15 percent. However, the contractor for the LCS Freedom class states that the LCS is capable of over 4000 nautical miles at cruise speed (Lockheed Martin 2012). If future operational testing proves that the LCS is able to exceed 4000 nautical miles, then it will well surpass the U.S. Navy's 3500 nautical miles requirement (O'Rourke 2015b).

Measuring the increase in ASW effectiveness by replacing the VDS with additional fuel storage is more complicated. An increase in endurance is an increase in mission effectiveness because more time is available for the mission as opposed to refueling. However, the loss of a sensor reduces mission effectiveness because less information can be gathered possibly meaning more time must be spent on mission. The team analyzed the effectiveness of the three sonar systems of the ASW mission package. Figure 22 shows the average performance against suspected threats of the three sonar systems in terms of range versus probability of detection. In this graph, both the VDS and the AQS-22 were calculated as active sonar systems and the MFTA was calculated as a passive system to match their use in the CONOPS in this report.

The AQS-22 system is by far the most effective of the three sonar systems. The other two systems are relatively equal in performance. While the VDS system does outperform the MFTA across the board, it is important to consider the CONOPS when determining mission effectiveness. Using PAMS, the LCS will only use active sonar while sprinting. One limitation of the Freedom sea frame is that it lacks the ability to utilize sonar systems at speed (Murphy 2010).

Murphy states as speed increases the depth of a deployed towed array decreases, reducing its effectiveness to make detections. Figure 29 visually demonstrates this

relationship between cable depth, length, and ship speed. In order to utilize active sources while transiting at speed, the LCS must use the AQS-22 equipped helicopters. Once the LCS reaches the start position, it can begin the drift operations. While drifting, the LCS will deploy passive sonar capabilities to establish a multi-static acoustic network. The MFTA is the primary passive sonar system for the ASW mission package. As such, losing the VDS does not greatly impact the ASW mission effectiveness. The AQS-22 and the MFTA effectively performs the bulk of ASW mission tasks in this report's proposed CONOPS.

Figure 29. Relationship of Cable Length and Depth in Critical Angle Towing
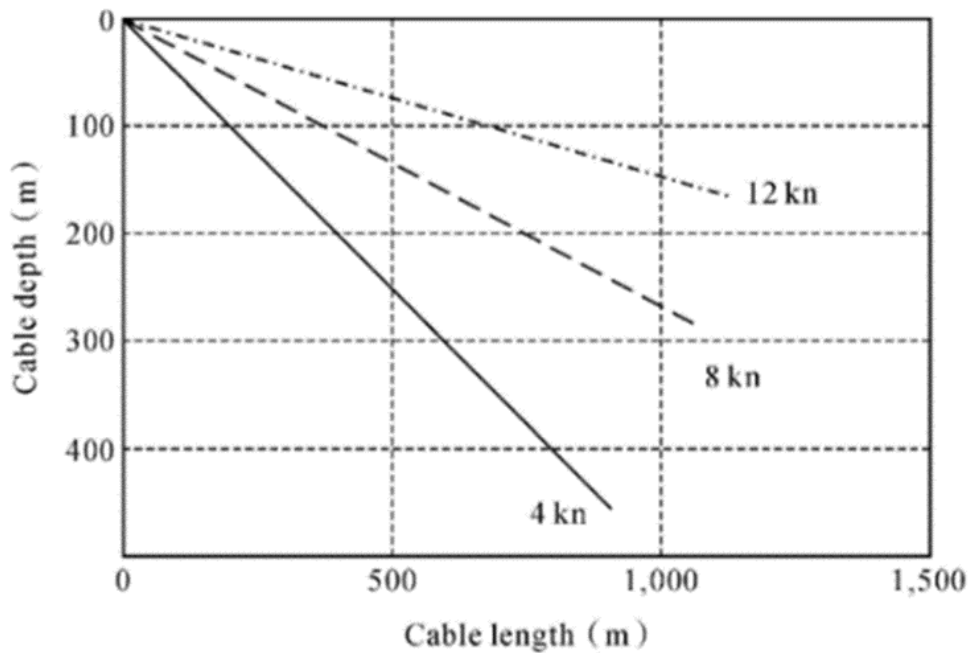
Source: Qihu Li, 1995, *Digital Sonar Design in Underwater Acoustics: Principles and Applications*, Hangzhou: Zhejiang University Press.

The best solution for range and endurance improvement will be a combination of both methods. The team's analysis shows decreasing the LCS's weight and adding more fuel storage will have positive results. The LCS is more capable if more fuel storage is added than by reducing total weight. Using careful throttle control and mixed-mode

transit increases fuel efficiency. The LCS could increase range by 22 percent by the combination of throttle control, mixed-mode transit and extra fuel storage.

D.   DATALINK CAPABILITY IMPROVEMENT

In order to address the datalink capability gap identified in this report, a higher bandwidth link that is compatible with current MH-60R aircraft is required. Thus, adding a Ku-band Tactical Common Data Link (TCDL) as well as an AN/SQQ-34 Aircraft Carrier Tactical Support System (CV-TSC) to the LCS is recommended. The Ku-Band TCDL permits high bandwidth and line of sight communications between an LCS and a MH-60R aircraft as illustrated in Figure 30 (Nilsen 2011). The greater bandwidth allows sending bulk sensor data such as acoustics, forward looking infrared video, and inverse synthetic aperture radar data.

The Ku-Band data link supports passing voice communications, contacts, tracks, fly-to-points, ship's position, and plan position indications (Nilsen 2011). Inclusion of CV-TSC will permit transferring sensor operator duties from the aircraft to the ship as well as improving the common tactical picture available to decision makers (Nilsen 2011). This advantage is achieved by the real-time data being made available directly to ship-board decision makers. CV-TSC facilitates integration of aircraft sensors with shipboard systems to detect, classify and localize ASW threats (Nilsen 2011). Additionally, CV-TCS can distribute and process sensor data, exchange tactical data with aircraft, exercise sensor control of off-board sensors, and reduce aircrew operator workload. These proposed improvements to the datalink and the processing of sensor data result in an improvement in the ability of LCSs to complete open-ocean ASW.

Figure 30.   Ku-Band Data Link and CV-TSC.

Source: Dean Nilsen, 2011, "Undersea Systems (IWS 5.0)," slides, Program Executive Office, Integrated Warfare Systems, Washington, DC.

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V. ALTERNATIVES ANALYSIS

A. COST COMPARISON BETWEEN LCS AND OTHER PLATFORMS

This team performed a cost comparison of naval vessels possessing an ASW capability to determine the relative cost associated with each vessel. The cost comparison includes research, development, procurement, operations, and support costs, as well as service life of the LCS, Virginia class submarines, Oliver Hazard Perry class frigate (FFG-7) and other surface combatants. The comparison utilizes the results of an independent life cycle cost comparison performed by the Government Accountability Office (GAO), which evaluated existing and former surface combatants to the LCS (United States Government Accountability Office 2014).

This team compared the life-cycle costs of the LCS to several other platforms, which are also capable of fulfilling ASW missions. Of particular interest was the comparison of procurement costs between an LCS and a Virginia class submarine. While the Virginia class possesses many capabilities that the LCS does not, the submarine cost is significantly higher than an LCS. The procurement cost of a Virginia class submarine in FY2014 dollars is $2,596 million (O' Rourke 2015c), while the procurement cost of an LCS equipped with an ASW module in FY2014 dollars is $567 Million according to a GAO report produced in 2014. Additionally, the anticipated useful life of an LCS is 25 years while the anticipated useful life of a Virginia class submarine is 33 years.

The LCS was also compared to FFG-7. Since the LCS will replace the FFG-7 (Freedberg 2015) this comparison is very important. Individual FFG-7 procurement costs were $579 million in FY 2014, according to 2014 GAO report. Table 8 compares the per-unit costs associated with LCS, MH-60R rotary winged aircraft, the Virginia class submarine and the retiring FFG-7.

Table 8.   Procurement Costs (in millions of FY2014 dollars)

	MH-60R	LCS	Virginia Class	FFG-7
Procurement	$33.00	$567.00	$2,596.00	$579.00
Service Life	22 years	25 years	33 years	33 years
Total Procurement costs/ Service Life	$1.50	$22.70	$78.70	$17.50
(LCS procurement cost provided above include mission module cost)				

Adapted from United States Government Accountability Office, 2014, *Deployment of USS Freedom Revealed Risks in Implementing Operational Concepts and Uncertain Costs*, Washington, DD: GAO.

The procurement costs, on a per-year-of-service-life basis (since the service life of the vessels differ significantly), of one Virginia class submarine is roughly equivalent to the procurement cost per-year-of-service-life costs of approximately three LCS vessels, each equipped with two MH-60R aircraft and the ASW mission module. Additionally, this analysis resulted in procurement costs-per-year-of-service life for the LCS including the mission module of $22.70 million/year, which exceed that of FFG-7 $17.50 million/ year.

In terms of manning requirements, the Virginia class submarine is staffed by 132 crew composed of 15 officers and 117 enlisted (Saunders 2007). The LCS requires 40 core crew sailors, 19 sailors attached to the mission package and 23 sailors in the aviation detachment that totals to 89 sailors (Littoral Combat Ship Manning Concepts 2013).   The FFG required a crew of 215 consisting of 13 officers and 202 enlisted (Schwartz 1981). Table 9 shows the manning requirements for the LCS, FFG-7 and Virginia class vessels.

Table 9   Manning Requirements for LCS, FFG-7 and Virginia Class

	LCS	Virginia Class	FFG-7
Officer	18	15	13
Enlisted	71	117	202
Total	**89**	**132**	**215**

Figure 31 provides the GAO independent life-cycle cost comparison between an LCS and other surface combatants (United States Government Accountability Office 2014). The GAO analysis resulted in a per year life-cycle cost (including research, development, procurement, operations, and support) of $79 million in FY2014 dollars. As Figure 31 illustrates, the LCS is estimated to be more expensive than Patrol Coastal Ships (PC-1), Mine Countermeasure Ships (MCM-1), and Frigates, yet be less expensive than both Cruisers (CG-47) and Destroyers (DDG-51).

Figure 31.   Per Year Life-Cycle Cost Comparison Estimate
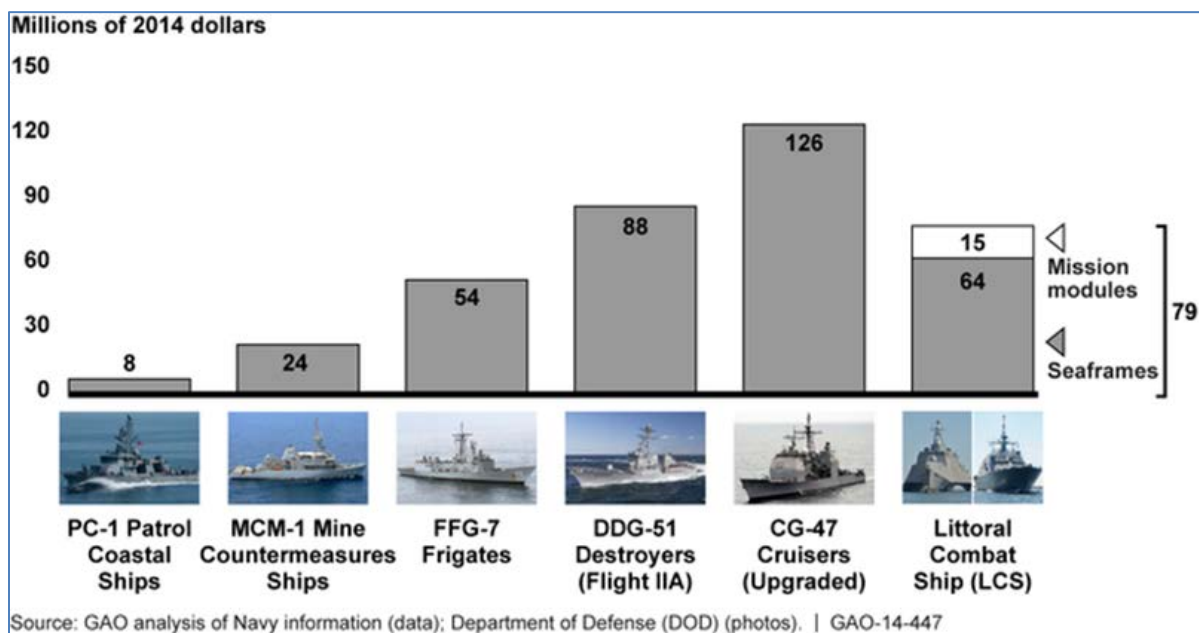
Source: GAO analysis of Navy information (data), Department of Defense (photos), in *Littoral Combat Ship,* 2014, GAO report 14-447, Washington, DC: U.S. Government Accountability Office.

The cost analysis yields favorable results for the LCS in terms of per year life cycle costs when compared to Cruisers, Destroyers, and Virginia class submarines. However, the LCS is costlier than the FFG-7 in per year life-cycle costs. Figure 32 provides an additional level of cost details for each type of surface combatant.

Figure 32.   Surface Combatant Life-Cycle Cost Comparison

	Navy surface ships estimates (based on actual data)					Littoral Combat Ship (LCS) estimates	
	PC-1 Patrol Coastal Ships	MCM-1 Mine Countermeasures Ships	FFG-7 Frigates	DDG-51 Destroyers (Flight IIA)	CG-47 Cruisers (Upgraded)	LCS seaframes[a]	LCS mission modules[b]
Number of ships/modules	13 ships	14 ships	51 ships	34 ships	22 ships	55 ships	64 modules
Life-cycle costs per ship/module	$243 million	$717 million	$1,607 million	$3,508 million	$4,410 million	$1,592 million	$449 million
• Research and development	0 million[c]	3 million	2 million	91 million	9 million	66 million	37 million
• Procurement	33 million	282 million	579 million	1,501 million	1,964 million	506 million	61 million
• Operations and support	210 million	432 million	1,026 million	1,916 million	2,436 million	1,013 million	292 million
• Other[d]	0 million	0 million	0 million	0 million	0 million	7 million	59 million
Expected service life	30 years	30 years	30 years	40 years	35 years	25 years	30 years
Average life-cycle cost per year[e]	$8 million	$24 million	$54 million	$88 million	$126 million	$64 million	$15 million
						$79 million	

Source: GAO analysis of Navy information (data), Department of Defense (photos), in *Littoral Combat Ship,* 2014, GAO report 14-447, Washington, DC: U.S. Government Accountability Office.

B.   LCS ENDURANCE COST TRADEOFF

Removing the VDS system from the LCS ASW mission package will reduce the overall life cycle cost of the package significantly, as it will no longer include the VDS in the procurement cost. According to the Department of Defense Fiscal Year (FY) 2017 President's Budget Submission Justification Book, procurement cost for a single VDS is nearly $13 million (Department of the Navy 2016). However, if the recommendation to remove the VDS from the ASW MP is not implemented until after mission packages are already installed, then there will be significant costs associated with uninstalling the VDS. There has been no demonstration of a removal of a VDS system from an LCS; therefore, there are no accurate projections for what this event may cost. A RDT&E Budget Item Justification report estimates it costs $4.2 million to:

Install CAS/VDS ADM on Littoral Combat Ship (LCS) platform and conduct at-sea testing of ADM. Continue efforts to mature ADM to EDM level. Continue independent critical review and analysis of alternatives of

selected and potential CNO ASW initiative technologies. (Department of the Navy 2013, 4)

While the Advanced Development Model (ADM) and Engineering Development Model (EDM) versions of the VDS for the LCS are not exactly what will be fielded, they should be representative. Furthermore, the removal of the final fielded VDS system should have a similar cost to the installation of the ADM unit.

The price of fuel determines the operational costs associated with implementing range and endurance improvements. The price of diesel fuel fluctuates. Most recent estimates calculate an average price for diesel globally at $0.83 per liter (GlobalPetrolPrices.com 2016). Replacing the VDS system with an equal weight of diesel will result in an increase of approximately $32,500 in fuel costs. Mixed-mode transportation does not require any modifications to the LCS platform (Burpa 2012). All fuel savings will be a direct reduction in operating costs. For a hypothetical six-month deployment, Burpa estimates a fuel savings of 35,000 gallons, which equates to a nearly an $110,000 savings in fuel costs. Combining both extra fuel capacity results in a total operational cost savings of $77,500 for a six-month deployment.

C. DATALINK IMPROVEMENT COST

The cost of the proposed improved datalink and CV-TSC console is difficult to estimate. The authors have first-hand knowledge of a shore installation of a CV-TSC console and accompanying datalink hardware. This shore installation cost was approximately $250,000.00. Assuming the more robust requirements of a shipboard system with double the price, results in $500,000.00 for installation and procurement of the improved datalink hardware.

D.   LCS VARIANT SELECTION

A Pugh matrix comparison, provided in Table 10, was used to evaluate the relative strengths and weaknesses of the LCS Freedom class, the LCS Independence class and the retiring FFG-7 class. The FFG-7 was used as the baseline because the LCS will replace the retiring frigates.

The LCS-1 Freedom class information used to assemble the Pugh matrix is available within a Lockheed Martin (2012) document titled "Freedom Variant Littoral Combat Ship: Full Speed Ahead." The LCS-2 Independence class information used within the Pugh matrix comes from an Austral corporation document, published in 2009 and titled "LCS 127." The FFG-7 Oliver Hazard Perry class Frigate information comes from a U.S. Navy Fact File, titled "Frigates-FFG," published in 2015.

The scoring of the Pugh matrix has five possible scores. A 0 indicates that the LCS is equal to that of the FFG-7 baseline for that category. A score of 1 indicates that the LCS variety is better than the base line. A 2 indicates that the LCS is much better than the baseline. A negative one (-1) indicates that the LCS is worse than the baseline and a negative two (-2) indicates that the LCS is much worse than the baseline. The FFG-7 receives a 0 in all categories because it is the baseline.

Table 10.   Variant Selection Pugh Matrix

	Category	FFG-7 Baseline	LCS-1 Freedom	LCS-2 Independence
ASW	Torpedo Countermeasure	0	1	1
	Equipment Deployment Ease	0	2	1
	Configurability (flexibility)	0	2	2
	Helicopter Capacity	0	0	0
	Acoustic Silencing	0	-2	-2
	Ease of Helicopter Operations	0	0	0
	Variable Depth Sonar	0	2	2
	Sensors(Towed array)	0	2	2
	Rotary Wing (RW) Torpedo	0	0	0
	Shipboard Torpedo	0	-2	-2
General	Speed	0	2	1
	Range	0	-1	-1
	Data Link	0	0	0
	Total		**6**	**4**

Both LCS variants are equipped with an updated version of the Light Weight Tow torpedo countermeasure. The FFG-7 was equipped with an older version of the Light Weight Tow torpedo countermeasure. Therefore, the LCS vessels each exceed the score of the baseline FFG-7 in the category of torpedo countermeasures.

Equipment deployment ease is largely a function of ship stern geometry. Both LCS variants are designed for deploying towed equipment and both are deemed to surpass the baseline FFG-7 baseline in this category. However, the LCS-1 variant receives a superior score because it possesses superior stern geometry for deploying towed equipment than LCS-2.

In terms of configurability, both LCS variants' design incorporates the modular principles to support mission packages. Therefore, both LCS variants are much better than the baseline, FFG-7.

Each of the three vessels compared within the Pugh matrix is capable of operating two rotary wing aircraft capable of launching torpedoes. Therefore, each LCS variant receives the same score as the baseline FFG-7 in terms of helicopter capacity and rotary wing launched torpedoes.

The FFG-7 design incorporated both sound isolation mounts and a radiated noise reduction system. Neither LCS variant possesses sound isolation mounts or a radiated noise reduction system. Therefore, the FFG-7 greatly surpasses both LCS variants in this category.

With regard to ease of helicopter operations, both LCS variants have been designed with aircraft operations as a high priority and are equivalent to the score of the baseline FFG-7.

In terms of both VDS and MFTA, each LCS variant can be equipped with both, while the FFG-7 possessed only an older model MFTA. Therefore, both LCS variants greatly exceed the score of the FFG-7 in each of these categories.

The FFG-7 possessed a shipboard torpedo while neither of the LCS variants does. Therefore, both LCS variants greatly underperform the baseline FFG-7 with regard to the shipboard torpedo category.

The sprint speed of LCS-1 is marginally greater than that of LCS-2 and both exceed the speed of FFG-7. Therefore, LCS-1 receives the highest score in the speed category and LCS-2 receives a marginally better than the baseline, FFG-7 score. Additionally, within the range category both LCS variants underperform the baseline, FFG-7 and are scored accordingly.

The datalink between aircraft and ship for each vessel compared is equivalent. Therefore, each vessel received the baseline score.

The LCS-1 has a marginal advantage over LCS-2 in two categories, first in the ease of towed equipment deployment, and second in sprint speed. Due to these two advantages, this team selected LCS-1 as the superior variant to perform open-ocean ASW.

E.   IMPROVED LCS COMPARISON

A Pugh matrix comparison, provided in Table 11, was used to evaluate the relative strengths and weaknesses of the proposed improved LCS-1 to the existing LCS Freedom class, and the retiring FFG-7 class. The FFG-7 was once again used as the baseline of the Pugh matrix.

Table 11.   Improved LCS Pugh Matrix

	Category	FFG-7 Baseline	LCS-1 Freedom	LCS-1 Freedom Improved
ASW	Torpedo Countermeasure	0	1	1
	Equipment Deployment Ease	0	2	2
	Configurability (flexibility)	0	2	2
	Helicopter Capacity	0	0	0
	Acoustic Silencing	0	-2	0
	Ease of Helicopter Operations	0	0	0
	Variable Depth Sonar	0	2	2
	Sensors (Towed array)	0	2	2
	Rotary Wing (RW) Torpedo	0	0	0
	Shipboard Torpedo	0	-2	-2
General	Speed	0	2	2
	Range	0	-1	0
	Data Link	0	0	2
	Total		**6**	**11**

The proposed improved LCS-1 variant incorporates three changes. It adopts the recommended acoustic silencing improvements described within Chapter IV. This results in an acoustic silencing similar to that of the FFG-7 baseline. It includes the range and endurance improvements detailed in Chapter IV, which results in a range comparable to the baseline, FFG-7. The improved LCS-1 utilizes the improved datalink and CV-TSC described in Chapter IV of this report. This provides a data link superior to that available with the baseline, FFG-7. These three improvements result in a more capable open-ocean ASW platform, as is illustrated by Table 10.

VI.   CONCLUSIONS

A.   FINDINGS

Through analysis of the problem space and the current capability gaps of the LCS in performing open-ocean ASW, this report makes recommendations for the improvements of the LCS. In addition, a cost analysis of the recommended improvements demonstrated that the recommendations are feasible.

1.   Operational Improvements

Exploiting active and passive sonar techniques with the combination of more than one ship requires the development of new CONOPS for open-ocean ASW when using the LCS. The acoustic model used in this report shows that open-ocean ASW is possible with the LCS. The CONOPS developed herein employs a team of LCSs combined with active and passive sonar techniques to take advantage of multistatic signal processing. Certain operational maneuvers, such as sprint and drift can be incorporated to accomplish sea denial missions.

2.   System Improvements

Certain capability gaps were identified that must be considered when utilizing the new CONOPS that were identified in this report. The capabilities addressed were acoustic silencing, excess weight, and datalink capabilities. In order for the new CONOPS developed to be effective, ownship noise needs to be controlled. The CONOPS would be worthless if enemy submarines could easily detect an LCS. Since littoral waters acoustically contain more noise and a higher level of sound than the open ocean, the LCS contains no acoustic silencing systems. Acoustic silencing features should be incorporated into the follow-on LCS design that will improve ownship noise and result in the LCS being difficult to detect by enemy submarines. The proposed CONOPS also involve the LCS sprinting and drifting, which require the LCS to have a large range and long on-station times. The current LCS weight limits the range and endurance and thereby limit the ability to accomplish open-ocean ASW. Simply removing certain

systems, such as VDS, from the LCS and adding in their place extra fuel storage all the range and endurance needed for open-ocean ASW can be achieved. Aircraft carried by the LCS are used to detect and engage enemy submarines. However, the constrained datalink capabilities limits the ability to accomplish this in a single sortie. Improving the datalink capabilities allows information and processing of contacts while aircraft are in flight. Shipboard sonar operators can receive acoustic data and other communications from aircraft in flight simultaneously passing information back to aircraft to prosecute enemy submarines.

B.   RESPONSE TO RESEARCH QUESTIONS

In order to conclude this report and provide the stakeholders with the information needed to make a decision, the responses to the research questions are summarized:

(1)   Which LCS variant performs open-ocean ASW better?

The Freedom variant is expected to perform ASW better than the Independence variant based on the information and analysis within this report. The Freedom has a greater speed than the Independence. The Freedom is also able to load equipment easier than the Independence.

(2)   What changes need to be made to the LCS to facilitate effective open-ocean ASW?

Several capability gaps were identified: acoustic control, range and endurance, and datalink capabilities. These gaps were addressed by noise reduction around the hull of LCS, internal sound isolation, ownship radiated noise awareness, weight reductions and extra fuel loading, throttle control and mixed-mode transits, and the inclusion of CV-TSC to the LCS. The potential acoustic, datalink, range and endurance improvements will mitigate these capability gaps.

(3)   How effective will the proposed solution be at open-ocean ASW?

Open-ocean ASW requires addressing all of the capability gaps this report identified. Without improvements in those areas, the LCS cannot effectively perform open-ocean ASW missions.

(4)   How much will the proposed solution cost?

While selection criteria for potential solutions did include cost and feasibility, insufficient data to address the cost of the proposed solutions with reasonable accuracy was found. Therefore, the authors leave developing cost of proposed solutions as an area for future study.

(5)   How much more effective will the proposed solution be compared to the current LCS platforms?

Any acoustic control improvement to the LCS would increase the effectiveness since no current systems are used. Increasing fuel storage and mixed-mode throttle control can increase range by 22 percent. Increased datalink capability can reduce aircraft detect to neutralize from two or more sorties to a single sortie.

C.   AREAS OF FUTURE STUDY

In order to improve the LCS for open-ocean ASW in addition to recommendations herein, future researchers should address continued effort and study of acoustic control, increased range capability, and a more robust datalink with aircraft. In addition, the cost associated with potential improvements requires further study.

The LCS uses a water jet propulsion system, and little work has been made on decreasing the acoustic signature of this system. This is investigation that future researchers should explore. Additionally, the traditional acoustic control systems currently available may not be compatible with a water jet system and compatibility should be evaluated. Reduction of radiated noise from on board systems and propulsion shall need to be addressed in order for open-ocean ASW sensors to be most effective.

During this study, the range of the LCS was considered a capability gap even if the requirement of 3500 nautical miles was met. When comparing the LCS to the frigate

(FFG-7), the LCS range was considerably less than that of the FFG-7. If the LCS is to replace the FFG-7, then the LCS needs to meet all the requirements of the frigate. To achieve this goal, this study explored reducing weight from the LCS by removing the VDS system and replacing VDS with extra fuel storage. It is unlikely that the VDS is fully utilized in the identified CONOPS.

The VDS was evaluated as an active sensor only but also has inherent passive capability. If the VDS is to be retained, the system's passive sensor effectiveness should be further investigated.

A final area of future research is further study of the data link. Data link bandwidth between the LCS and aircraft was insufficient and considered a gap for this study. As sensor resolution increases, the bandwidth required between aircraft and LCS will increase. Therefore, a robust, high bandwidth data link is a paramount concern for LCS vessels conducting operations with aircraft.

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